THE INVESTIGATION OF RIVERS

FINAL REPORT

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THE INVESTIGATION OF RIVERS—FINAL REPORT.

By AUBREY STRAHAN, Sc.D., LL.D., F.R.S., N. F. MACKENZIE, M.Inst.C.E., H. R. MILL, D.Sc., LL.D., and J. S. OWENS, M.D., A.M.Inst.C.E.

INTRODUCTION.

By A. STRAHAN, Sc.D., LL.D., F.R.S.

This investigation was commenced in 1906 by aid of a Government grant of £150 per annum for three years from the Royal Society, supplemented by a grant of £50 by the Royal Geographical Society. The object in view was an examination of certain rivers in England and Wales for the purpose of ascertaining—

(*a*) The discharge in winter and summer, and the total annual discharge.

(*b*) The suspended and dissolved matter in wet and dry periods, the total amount carried in the year, and the erosion of the land-surface in tons and depth of inches.

(*c*) The rainfall in different parts of each basin, and the average rainfall over the whole basin.

(*d*) The area of each basin, and the elevation of different parts of it. The area occupied by calcareous and non-calcareous formations, and by pervious and impervious formations.

At my invitation the late Dr. A. J. Herbertson and Dr. H. R. Mill joined me as a committee, the latter undertaking to furnish records of the rainfall. Subsequently Mr. N. F. MacKenzie consented to become a member of the committee, and to give the benefit of his wide experience in gauging rivers and canals in India. To Dr. J. S. Owens we became indebted for working out the valuable records of discharge of the Severn, which had been obtained and placed at our disposal by the late Dr. G. F. Deacon, and for dealing with the rainfall statistics, while Mr. Sellick, under Dr. Owen's superintendence, traced on the ground the limits of the basin of that river wherever it was necessary to do so. The periodical determination of the amounts of suspended and dissolved matter in the water was kindly undertaken by Mr. W. H. Lewis as regards the Exe, by Mr. R. C. Willis, and subsequently by Mr. A. N. Fitzgerald, as regards the Medway. The Severn water was similarly dealt with by the late Dr. G. H. Woollat and Mr. C. W. Marshall.

To the Exeter City Council we are indebted for permission to erect gauges and to employ some of their men to read them. Mr. Thomas Moulding, the City Surveyor, has given great assistance, and has also furnished the valuable records of dredgings referred to later on. The reading of the gauge at Silverton was kindly undertaken and carried out continuously by Mr. Charles Gray, engineer to the Silverton Mills. The limits of the river-basin were traced by Mr. Elton and Mr. Beckit, and the measurements of areas were made chiefly by Mr. Elton, with some subsidiary measurements by Mr. Carter and Mr. Beckit.

By the kindness of Mr. F. J. Tracy, we were permitted to fix a gauge at his

Exe Valley fishery, and to employ his foreman for keeping the records. On the Medway, Mr. Randall Mercer and Mr. W. E. Martin were kind enough to allow the erection of automatic clock-gauges in a boathouse and in a garden respectively. Among other innumerable matters which arose for consideration during the progress of the investigation, mention may be made of levelling, of velocity observations, and of constant attention to the clock-gauges. The levelling, as far as regards the Exe, was performed by Mr. Elton and Mr. Beckit, while that on the Medway, where greater precision was required than local surveyors were willing to undertake, was carried out by Mr. MacKenzie, who in this matter and in the ceaseless trouble given by the clocks had the assistance of Lieut.-Gen. Charles Strahan, R.E. The area of the Medway basin was measured by Mr. E. W. Dann.

The committee desire to express their obligation also to the Lower Medway Navigation Company. By permission of the Chairman, Mr. John Arkcoll, the site in the boathouse was prepared by their staff, under the superintendence of Mr. John Rose, the lock-keeper at Allington.

In selecting the Exe, Medway, and Severn for examination, the committee were influenced by several considerations. It was desirable to make the choice from among the larger rivers of the country. At the same time it seemed likely that it would add much to the completeness of the results if river-basins representative of the different geological conditions which prevail in the east of England, and in Wales and the west of England respectively, could be compared. The Thames has so long been made the subject of observations with more or less the same objects in view, that it was decided to choose a less-frequented river. The Bedfordshire Ouse was considered, but was rejected on the score that in the lower part of its course it is divided up into so many natural and artificial channels that it was beyond our power to ascertain the total discharge. The Medway was eventually selected as one of the larger rivers draining an area of Mesozoic strata, though from the first difficulties in obtaining an accurate discharge were anticipated. As regards the West Country, the Exe appeared suitable, both from its volume and from the fact that it drains an area consisting in the main of Palæozoic rocks. The Severn was added to the list subsequently, not only on account of its importance, but for the purpose of utilizing the important records obtained by Dr. Deacon. It had been intended to include also a typical chalk-river. Results of great interest might have been expected, and the Salisbury Avon was under consideration as a suitable example, but the work had not been commenced when the necessity for closing the investigation arose.

REPORT ON SEVERN DISCHARGE AND RAINFALL IN THE BASIN.

By J. S. OWENS, M.D., A.M.Inst.C.E.

The gaugings of the discharge of the river Severn at Worcester for the years 1881 to 1889 were placed at the disposal of the committee by the late Dr. G. F. Deacon. The method adopted for measuring the discharge was described by Mr. H. T. Turner in the *Proc. Inst. C.E.*, vol. **80**, 1884–5, p. 318, to which reference should be made. The site selected was on a straight stretch half a mile in length, and about 1 mile above Diglis weir at Worcester. The river is 180 feet wide, and when bank full about 25 feet deep in the middle. Two poles, 50 feet in height, were placed one on each side of the river, and between them was stretched a wire, upon which travelled a small carriage. From the carriage an electric current-meter could be lowered at any position in the cross-section, and to any depth in the river. The observations were made at intervals of 10 or 20 feet across the

channel, and at intervals of 1 foot in depth. "The observed velocities past each vertical were plotted to a large scale on a diagram, so as to form velocity-curves at each point whose areas represented the discharges past the respective vertical. . . . Altogether fifteen series of observations were made, and their results were plotted to a curve. From this curve was constructed a discharge-scale, giving the rate, in million gallons per day, corresponding with the staff-gauge reading used for computing the daily flow of the river from the diagrams of an automatic gauge."

In order to utilize this valuable series of measurements, extending over a period of eight years, for the purpose of bringing out the relations between the rainfall and the discharge, it was necessary to obtain the rainfall statistics. Dr. H. R. Mill kindly provided carefully checked records from all the available rain-gauges in the basin for the required period.

It appeared probable that, if curves showing the daily discharge of the river and the daily rainfall in the basin above the point at which the discharges were measured, could be plotted together on the same base and in the same units, the comparison would be instructive. For example, the general relation between rainfall and evaporation, percolation and run-off would be apparent. It was further anticipated that many of the peaks on the rainfall-curve would not appear on the discharge-curve; also, that when corresponding peaks did appear on both, the discharge-peak would show a time-lag as compared with the rainfall-peak. Again, since in each case the total volume of water for any period would be represented by the area of the curve for that period, the intercepted area between the curves would represent the loss by evaporation and percolation. It would also be possible, when the final figures were available, to compare rainfall and run-off in the ordinary way by calculation, showing the latter as a percentage of the former.

The work thus divided itself naturally into two distinct sections, one dealing with the rainfall, and one with the run-off or discharge; and as much preliminary work was necessary before it was possible either to plot the curves or make any final calculations, the subject will be dealt with under those two distinct headings.

River Discharge.

The original figures for the discharge were given in millions of gallons per day, there being five readings for each day for the whole period 1881 to 1889, with the exception of such interruptions as were due to floods or accident. The first operation was therefore to convert the five daily readings into one representing the average for each twenty-four hours. It was further considered that the unit of measurement should be altered to cubic feet per second. Having made these two changes, the discharge figures were next plotted for the eight years, showing one reading per day. One such curve for the year 1882 is reproduced in Plate 1. Curves were also plotted showing the mean monthly discharge, Plate 2, Fig. 1; mean discharge for six months, Plate 2, Fig. 2; and mean discharge for each year, Plate 2, Fig. 3.

Rainfall.

The object in view was to find a method of obtaining the total daily rainfall in the part of the river-basin above Worcester, where the discharge of the river was measured, for the period 1881 to 1889 for which the discharge-measurements were available. As already stated, it was intended to plot the rainfall and discharge in the same units and on the same base; hence, since rainfall is measured in inches of depth, a part of the work consisted in converting inches per day into cubic feet per second, the latter being the unit decided on. In what follows the word "cusec" will be used to mean cubic feet per second.

Several methods of finding the total daily rainfall were carefully considered, and before going into these it will be well to state precisely the problem which had to be dealt with. Carefully checked rainfall sheets for the whole eight years were supplied by Dr. Mill. These showed the daily readings for something like an average of forty gauges for each year, or about 117,000 separate readings to be dealt with. There were, however, two chief difficulties to be faced :—

1. The rain-gauges were unevenly distributed over the basin ; in certain large areas there were none, while at other parts a number were concentrated within a small space.

2. The gauges for which readings were available varied in number from year to year, so that in no two years were the same group of gauges available. In fact, few of the gauges were read continuously for the whole eight years under consideration.

We have, therefore, to cope with irregular distribution in both time and space. Obviously, absolute accuracy of results is not to be hoped for under such circumstances ; but an accuracy within, say, 5 per cent. of the true figures was considered to be of sufficient value to be aimed at.

The following possible methods were considered :—

1. Adding all the available gauge-readings on any day, and dividing by the number of gauges to obtain an average for the basin. This method would clearly give fallacious results unless the gauges were uniformly distributed, a condition which was not fulfilled.

2. Out of the total number of gauge readings on any day a certain number might be selected, choosing them so that the selected gauges were as uniformly distributed over the basin as possible. The sum of the readings of the selected gauges divided by their number might then be taken as giving the mean rainfall over the whole basin. The chief objection to this appears to be that the more sparsely gauged districts would determine the distance apart of the gauges to be selected, and thus a great many gauges would have to be omitted ; probably not more than 50 per cent. of the available data would thus be utilized, with a consequent loss of accuracy, unless the gauges were originally numerous and evenly distributed.

3. The plan of the basin might be divided into small squares of such size that at least one gauge would be contained by each square. The rainfall in each square might then be calculated from its enclosed gauges, and the sum would give the total rainfall in the basin. The method involves the error of assuming the rainfall in a square to be given fairly by perhaps only one gauge. This would not be serious if the squares were small enough ; but as, under ordinary circumstances, the squares would have to be large owing to scarcity of gauges in some parts of the basin, this error would probably be considerable.

4. A rainfall-map of the basin might be made for each year, then the daily readings of the gauges lying between each pair of isohyets averaged, this average being taken as giving the mean daily rainfall for the area enclosed between the isohyets. By treating each area thus, and adding the totals for such areas, the total for the basin might be got. This, however, assumes the rainfall distribution for the year to be the same as that for each day, which is not true. It would obviously be impracticable to make a rainfall-map for each day, as this would imply an enormous number of maps ; but, if this were done, it would doubtless give an accurate result, and one in which all available data would be utilized.

5. The available gauges in any year might be separated into groups so arranged that the "centres of gravity" of the groups were uniformly scattered over the basin and the long axes of the groups as far as possible parallel to the isohyets. The average of all the daily readings of the gauges in a group being taken for each

group, the sum of these divided by the number of groups would give fairly the mean for the basin.

After carefully considering the above possible methods it was finally decided to adopt No. 5. The various steps in applying this method were as follows: Every gauge available was marked on the $\frac{1}{4}$-inch map of the basin, with a number corresponding to that which it bore in the record-sheets. In this way eighty-three gauges were marked in, and it was found, as stated above, that they tended to group themselves round certain points, leaving large areas of the basin unrepresented, except, perhaps, by a single gauge. The boundary of the river basin was then transferred to the map.

The next step was to group the gauges for each year in such a way that the centres of gravity of the groups were as uniformly scattered over the basin as possible. Thus, one group might contain twelve or thirteen gauges and another only one, the average in a group being about five or six. In this way from seven to ten groups were arranged for each year, utilizing all the gauges read in that particular year. The daily average of each group was then taken and used as if it represented the reading of an imaginary gauge situated at the centre of gravity of the group. By doing this all the gauges read in any year were reduced to from seven to ten group-averages; and since the groups were so chosen as to give a uniform distribution of their centres of gravity over the basin, the rainfall of the whole basin could be obtained by simply taking the average of these seven to ten representative imaginary gauges, and multiplying it by the area of the basin. In this way not only could all gauges be utilized, but the grouping tended to reduce the effect of errors in the individual records. The long axes of the groups were arranged so as to be parallel to the isohyets when the gauges of a group were irregularly distributed in the group, otherwise this precaution was unnecessary.

Having fixed the groups for each year the next step was to construct tables from which to obtain the averages of the groups and the basin, and to transfer to these the readings on the record sheets supplied by Dr. Mill. There were on the average about forty gauges read in each year, giving 40×365 readings, which for the eight years of records gives 116,880 separate readings to be entered up, added and averaged as above described.

The map of the basin, Plate 3, Fig. 1, shows a typical year's grouping of the gauges; ordinary gauges are shown by round dots, and the centres of gravity of the groups by square dots with flags. This method of treatment involved a great amount of tabulation and calculation. Table I. shows an ordinary rainfall sheet as received from Dr. Mill. Table II. shows the arrangement adopted for dealing with these figures. Summarized, these steps were as follows :—

(*a*) Group gauges for each year as described.

(*b*) Add the readings of each group and divide by number of gauges in group.

(*c*) Add the averages from (*b*) and divide by number of groups in (*a*).

(*d*) Multiply the mean from (*c*) by area of basin to get total for the day.

(*a*) Must be done once for each year, (*b*), (*c*) and (*d*) once for each day.

As the rainfall on the record sheets was given in inches per day, and it was intended to convert this into cusecs, a constant was found which, when multiplied by the average rainfall over the whole basin in inches per day, gave the fall in cubic feet per second, or cusecs :—

If I represents the average rainfall on the basin in inches per day of 24 hours,

C the same in cubic feet per second, and

A the area of the basin in square miles,

then $$C = 26{\cdot}89AI$$

TABLE I.

REGISTER OF RAINFALL IN 1889.

Kept at

in the County of

by

RAIN GAUGE { Pattern
Diameter of top in.
Ht. of top above ground ft. in.
" " sea-level ft.

Time of observation

Nearest railway station { Name
Distance Direction

IMPORTANT NOTE.—Rain should be measured daily at 9 a.m., and the result entered to the previous day. If an Observer prefers not to conform to this almost universal rule, he is earnestly requested to add the reading at 9 a.m. on January 1 of the following year in the space provided for it at the end of this paragraph. Full instructions for the measurement of rain, the selection and placing of rain gauges, and particulars as to the British Rainfall Organization are given in "Rules for Rainfall Observers," sent post-free on application to Dr. H. R. Mill, 62, Camden Square, London, N.W.

Date.	Jan.	Feb.	Mar.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Date.
	inch.	inch.	inch.	inch.	inch.	inch.	inch.	inch.	inch.	inch.	inch.	inch.	
1	·04	·03	—	—	·09	·23	—	·03	—	—	·07	—	1
2	—	·17	—	·17	—	·06	—	·16	·07	·04	·15	—	2
3	—	·09	·03	·24	·05	—	—	—	·11	·03	·01	—	3
4	—	—	·01	·19	—	—	—	·17	—	·16	—	—	4
5	—	—	—	·01	·41	—	—	·11	—	·04	—	—	5
6	—	·27	·15	·09	—	—	—	·12	—	·31	—	·34	6
7	—	·02	·47	·51	·45	—	—	·06	—	·13	—	—	7
8	·13	·09	1·19	1·47	·30	·12	·02	·16	·01	·15	—	·22	8
9	·17	—	—	·47	·70	·06	·48	·29	—	·01	—	—	9
10	—	·50	—	·81	—	—	·64	·28	—	—	—	·12	10
11	—	—	·04	—	·55	—	—	·05	—	—	·02	—	11
12	—	·04	·01	·05	·09	—	·01	—	—	—	—	·23	12
13	—	—	—	·03	—	—	2·96	·04	—	·06	—	—	13
14	—	·09	·07	—	—	—	·01	·09	—	—	·08	·04	14
15	·03	·04	—	—	—	—	·01	—	—	·08	—	—	15
16	·04	·10	—	—	—	—	—	·16	—	·12	·08	—	16
17	—	—	—	—	·08	—	·05	—	—	·04	—	—	17
18	—	—	—	—	—	—	—	—	—	·15	—	—	18
19	·06	—	·10	—	—	—	·29	·35	·12	·28	—	·20	19
20	·02	·04	·21	·01	—	—	·20	—	·01	·12	—	·10	20
21	—	—	—	·10	—	—	·02	·30	·08	·06	—	·18	21
22	—	—	—	—	—	—	·05	·04	—	·34	·38	·16	22
23	—	—	·05	·52	·06	—	·21	·24	·85	·09	·03	·18	23
24	—	—	·03	·15	·44	—	·12	·10	·07	·02	·21	·02	24
25	—	·01	—	—	—	—	·01	·04	—	—	·04	—	25
26	—	·01	—	·03	·19	—	—	—	—	—	·05	—	26
27	·03	·03	—	·05	·05	—	—	—	—	·39	—	—	27
28	·07	·01	·11	·07	·18	—	—	—	·04	·05	—	—	28
29	·06	—	—	·20	·28	—	—	—	·07	·01	·02	—	29
30	·03	—	·05	·45	·43	—	—	—	—	·14	—	—	30
31	·01	—	·01	—	·05	—	—	—	—	·21	—	—	31
Total	·69	1·54	2·53	5·62	4·40	·47	5·08	2·79	1·43	3·03	1·14	1·79	Total for year 30 51
No. of Rain Days.	12	16	15	20	17	4	15	19	10	24	12	11	175

SEVERN: TABLE II.

DAYS OF THE MONTH.

METHOD OF DEALING WITH GAUGE GROUPS FOR TYPICAL MONTH, JANUARY, 1889.

Gauge No.	1.		2.		3.		4.		5.		6.		7.		8.	
29	—		—		—		—		—		—		—		·01	
30	·06		—		—		—		—		—				·35	
33	·01		—		—		—		—		—		·02		·16	
66	—		—		—		—		—		—		—		·13	
	·07	·017	·00	·00	·00	·00	·00	·00	·00	·00	·00	·00	·02	·005	·65	·162
31	·06				—				—		—				·21	
37	—		—		—				—		·02		—		·22	
	·06	·030	·00	·00	·00	·00	·00	·00	·00	·00	·02	·010	·00	·00	·43	·215
38	—		—		—		—		—		—		·09		·11	
69	·01						—		—						·06	
	·01	·005	·00	·00	·00	·00	·00	·00	·00	·00	·00	·00	·09	·045	·17	·085
7	—		—						—		—		—		·04	
51	·02		—		—		—		—		—		—		·04	
52	—		—		—		—		—		—		—		—	
64	—		—		—		—		—		—		—			
65	—		—		—		—		—		—		—		·03	
	·02	·004	·00	·00	·00	·00	·00	·00	·00	·00	·00	·00	·00	·00	·11	·022
3	·02						—		—		—		·01		·13	
31	—		—				—		—		—		·14		·13	
67	·01		—				—		—		·01		—		·03	
68	—		—		—		—						—		·11	
	·03	·007	·00	·00	·00	·00	·00	·00	·00	·00	·01	·002	·15	·037	·40	·100
2	·04		—		—		—						—		·13	
40	·03		—		—		—				—		—		·02	
45			—		—		—		—		—		·04		—	
48	·02		—		—				—		—		·02		—	
	·09	·022	·00	·00	·00	·00	·00	·00	·00	·00	·00	·00	·06	·015	15	·037
8	·04		—						—		—				·06	
10	·03		—						—		·01				·06	
41	·03		—				—				—		·03		·05	
42	—		—		—		—		—		—		·04		·10	
43	—		—		—		—		—		—		—		·11	
44	—				—		—		—		—		·03		·10	
	·10	·017	·00	·00	·00	·00	·00	·00	·00	·00	·01	·001	·10	·016	·48	·080
12	·01		—		—		—		—		—		—		·03	
13	·05		—		·02		—		—				—		—	
14	—		—		—		—		—		—		—		·09	
50	—		—		—		—		—		—		—		—	
54	·03		—		—				—		—		—		·03	
	·09	·018	·00	·00	·02	·004	·00	·00	·00	·00	—	—	—	—	·15	·03
18	—		—				—		—				—		·07	
20	·01		—		—		—		—		—		—		·08	
21	—		—		—		—		—		—		—		·07	
23	—		—		—		—				—		·03		—	
24	—		—		—		—		—		—		—		·07	
25	—				—		—		—		—		—		·04	
27	—				—		—		—		—		—		·07	
28	·01		—		—		·01		·01		—		·01		·03	
55	—		—		—		—		—		—		—		—	
56	·09		·13		·02		·04		—		·02		·01		—	
57	—				—		—		—				·03		·07	
59	—		—		—		—		—		—		—		—	
60	—		—		—		—		—		—		·03		·19	
	·11	·008	·13	·010	·02	·001	·05	·004	·01	·001	·02	·001	·11	·008	·69	·053
49	·01		—		—		—		—		—		—		—	
53	—		—		—		—		—		—		—		·04	
	·01	·005	·00	·00	·00	·00	·00	·00	·00	·00	·00	·00	·00	·00	·04	·02
Total of Means	—	·133	—	·010	—	·005	—	·004	—	·001	—	·014	—	·126	—	·804
Average for each day	·0133		·0010		·0005		·0004		·0001		·0014		·0126		·0804	

Gauge No.	9.		10.		11.		12.		13.		14.		15.		16.	
29	·54		·03		—		—		—		—		—		·02	
30	·33		—		—		—		—		—		—		·10	
33	·26		—		—		—		·01		—		—		·03	
66	·44		—		—		—		—		—		—		—	
	1·57	·392	·03	·007	·00	·00	·00	·00	·01	·002	·00	·00	·00	·00	·15	·037
31	·36		·02		—		—		—		—		—		·03	
37	·25		·01		·01		—				—		—		·02	
	·61	·305	·03	·015	·01	·005	00	·00	·00	·00	·00	·00	·00	·00	·05	·025
38	·28		—		—		—		—		—		—		·04	
69	·44		·05		—		—		—		—		—		—	
	·72	·36	·05	·025	·00	·00	·00	·00	·00	·00	·00	·00	·00	·00	·04	·020
7	·06		—		—		—		—		—		—		·06	
51	·12		·02		—		—		—		—		—		·06	
52	—		·14		—		—		—		—		—		·06	
64	·25		—		—		—		—		—		—		·08	
65	·15		—		—		—		—		—		—		·10	
	·58	·116	·16	·032	·00	·00	·00	·00	·00	·00	00	·00	·00	·00	·36	·072
3	·14		—		—		—		—				—		·02	
31	—		—		—		—		—		—		·03		—	
67	·41		·02		—		—		—		—		—		·02	
68	·36		—		—		—		—		—		—		·04	
	·91	·227	·02	·005	·00	·00	·00	·00	·00	·00	·00	·00	·03	·007	·08	·02
2	·17		—		—		—		—		—		·03		·04	
40	·11		—		—		—		—		—		—		—	
45	·16		—		—		—		—				—		·04	
48	·09		·02		—		—		—		—		—		·04	
	·53	·132	·02	·005	·00	·00	·00	·00	·00	·00	·00	·00	·03	·007	·12	·030
8	·14		—		—		—		—		—		—		·05	
10	·18		—		—		—		—		—		·01		·01	
41	·14		·01		—		·01		·01		—		·01		·04	
42	·23		·01		—		—		—		—		·02		·02	
43	·22		—		—				—		—		—		·05	
44	·09		—		·02		—		·01		—		·01		·05	
	1·00	·166	·02	·003	·02	·003	·01	·001	·02	·003	·00	·00	·05	·008	·22	·036
12	·19		—		—		—		—		—		—		—	
13	·11		—		—		—		—		—		—		—	
14	·14		—		·01		—		—		—		—		—	
50	·17		—		—		—		—		—		—		—	
54	·14		—		—		—		·06		—		—		·02	
	·75	·150	·00	·00	·01	·002	·00	·00	·06	·012	·00	·00	·00	·00	·02	·004
18	·25		—		·01		—		·03		—		—		—	
20	·34		·01		—		·03		·01		—		—		·02	
21	·28		·01		—		·03		·02		—		—		—	
23	·33		—		—		·04		·02		—		—		·02	
24	·40		—		—		·08		·03		—		—		·03	
25	·17		—		—		·04		·01		—		—		·02	
27	·17		—		—		·04		—		—		—		—	
28	·51		—		—		·07		·01		—		—		02	
55	·50		—		—		—		—		—		—		—	
56	—		·02		·01		—		·01		—		—		—	
57	·26		—		—		·03		·01		—		—		·02	
59	·31		—		—		·03		—		—		—		—	
60	—		—		·01		·04		·01		—		—		—	
	3·52	·271	·04	·003	·03	·002	·43	·033	·16	·012	·00	·00	·00	·00	·13	·01
49	·35		·01		·01		·10		·02		—		—		·02	
53	—		.02		·06		—		—		—		—		—	
	·35	·175	·03	·015	·07	·035	·10	·050	·02	·01	·00	·00	·00	·00	·02	·01
Total of Means	—	2·294	—	·110	—	·047	—	·084	—	·039	—	·000	—	·022	—	·264
Average for each day	·2294		·0110		·0047		·0084		·0039		·0000		·0022		·0264	

Gauge No.	17.		18.		19.		20.		21.		22.		23.		24.	
29	·01		·09		·18		·01		·02		—		—		—	
30	—		·02		·01		—		—		—		—		—	
33	·01		·11		·05		·01		—		—		—		—	
66	·03		·04		·05		·06		—		—		—		—	
	05	·012	·26	·065	·29	·072	·08	·02	·02	·005	·00	·00	·00	·00	·00	·00
31	—		·07		·07		·04		·01		—		—		—	
37	02		·06		08		16		—		·01		—		—	
	·02	·010	·13	·065	·15	·075	·20	·10	·01	·005	·01	·005	·00	·000	·00	·000
38	·06		—		—		—								—	
69	·03		·09		·10		·28		·02		·01					
	·09	·045	·09	·045	·10	·05	·28	·140	·02	·010	·01	·005	·00	·000	·00	·000
7	·01		—		·07		·02				—		·02		—	
51	—		—		·10		—		—		—		—		—	
52	—		—		·11		—		—		—				—	
64	·02		—		·05		—		—		—		—		—	
65	—		·01		·08		·03		—				—		—	
	·03	·006	·01	·005	·41	·082	·05	·010	·00	·000	·00	·000	·02	·004	·00	·00
3	—		·03		—		·05		—		·01		—		—	
31	·03		·02		·03		—		—		·01		—		—	
67	—		·01		·01		·03		—		—		—		—	
68			·06		·03		·03		—				—		—	
	·03	·007	·12	·03	·07	·017	·11	·027	·00	·00	·02	·605	·00	·00	·00	·00
2	—		—		·06		·02		—		—		—		—	
40	—		—		·03		·04		—		·02		—		—	
45	—		·03		—		·03		—		·01		—		—	
48	—		·01		·01		·04		—		·01		·01		—	
	·00	·00	·04	·010	·10	·025	·13	·032	·00	·00	·04	·010	·01	·002	·00	·000
8	—		·01		03		—		—		—		·01		—	
10	—		·05		·03		·03				·01		·01		—	
41	—		·06		·03		·03		—		·01		·01		·01	
42	—		·02		·05		—		·01		—		—		—	
43			·05		·03		·02		—		—		—		—	
44	—		—		—		·04		—		—		—		·01	
	·00	·00	·19	·031	·17	·028	·12	·020	·01	·001	·02	·003	·03	·005	·02	·003
12	—		—		·01		—		—		—		·01		—	
13	·03		—		·02				—		—		·02		·01	
14	·02		—		·05		—		—		—		·01		—	
50	—		—		—		—		—		—		—		—	
54	—		—		·01		—		—		—		—		—	
	·05	·010	·00	·00	·09	·018	·00	·00	·00	·00	·00	·00	·04	·008	·01	·002
18			·01		·06		·05				—		·01		·01	
20	—		—		·02		—		—		—		—		—	
21	—		—		—		·03		—		—		—		·01	
23	—		—		—		·02		—		—		—		—	
24	—		—		·03		—		—		—		—		—	
25			—		·02		—		—				—		·01	
27			—		—		—		—				—		—	
28			·01		·01		—		—		—		·02		—	
55	—		—		·08		—		—		—		—		—	
56	—				—		·19		—		—		—		—	
57	·02		—		·02		·01		—		—		—		—	
59	—		—		·01		—		—		—				—	
60	—		—		—		—		·04		—		—		·02	
	·02	·001	·02	·001	·25	·018	·30	·023	·04	·003	·00	·00	·03	·002	·05	·004
49	—				·03		·01		·01		·01		·01		·01	
53	—		—		·03		—				—		—		—	
	·00	·00	·00	·00	·06	·03	01	·005	·01	·005	·01	·005	·01	·005	·01	·005
Total of Means	—	·091	—	·252	—	·415	—	·377	—	·029	—	·033	—	·026	—	·014
Average for each day	·0091		·0252		·0415		·0377		·0029		·0033		·0026		·0014	

Gauge No.	25.		26.		27.		28.		29.		30.		31.	
29	—		·05		—		·26		·56		·19		·68	
30	—		—		·02		·12		·13		·10		·14	
33	—		—		·09		·26		·61		·24		·23	
66	—		—		—		·12		·26		·13		·15	
	·00	·00	·05	·012	·11	·027	·76	·190	1·56	·390	·66	·165	1·20	·30
31	—		—		·05		·23		·54		·12		·37	
37	—		·01		·03		·29		·53		·26		·09	
	·00	·000	·01	·005	·08	·04	·52	·26	1·07	·535	·38	·190	·46	·230
38	—		—		·08		·09		·10		·56		·12	
69			0·5		·05		·24		·35		·21		·05	
	·00	·00	·05	·025	·13	·065	·33	·165	·45	·225	77	·385	·17	·085
7	—		·04		·02		·03		·06		·04		·03	
51	—		—		—		·06		·09		·08		—	
52	—		—		—		—		—		—		·03	
64	—		—		—		—		·10		·07		·03	
65	—		·02		—		—		·04		·07		·03	
	·00	·00	·06	·012	·02	·004	·09	·018	·29	·058	·26	·052	·12	·024
3	—		—		·02		·02		·08		·07		·02	
31	—		—		—		·04		·09		·15		·04	
67	—		—		·02		·02		·10		·11		—	
68	—		—		·02		·06		·17		·10		·03	
	·00	·00	·00	·00	·06	·015	·14	·035	·44	·110	·43	·107	·09	·022
2	—		—		·03		·07		·06		·03		·01	
40	—		—		—		—		·10		·06		·03	
45	—		·01		—		—		·12		·08		·02	
48	—		—		·02		·03		·05		·02		—	
	·00	·00	·01	·002	·05	·012	·10	·025	·33	·082	·19	·047	·06	·015
8	—		·02		—		—		·09		·01		·02	
10	—		—		·02		·01		·12		·07		·01	
41	—		·02		—		·02		·10		·08		—	
42	—		—		·03		·03		·15		·03		·01	
43	—		—		—		·07		·06		·05		—	
44	—		—		—		·03		·07		—		·03	
	·00	·00	·04	·006	·05	·008	·16	·026	·59	·098	·24	·04	·07	·011
12	—		·01		—		—		·08		·01		·04	
13	—		—		—		·02		·11		—		·03	
14	—		—		—		—		·10		·02		·04	
50	—		—		—		—		·15		—		·04	
54	—		—		—		—		·09		·03		·03	
	·00	·00	·01	·002	·00	·00	·02	·004	·53	·106	·06	·012	·18	·136
18	—		—		·02		·01		·02		—		·01	
20	—		—		·02		·01		·05		·01		—	
21	—		—		—		·02		·10		—		—	
23	—		—		·02		—		·08		·03		—	
24	—		·01		—		·01		·08		·04		—	
25	—		—		—		·02		·09		·03		·01	
27	—		—		—		—		·19		·03		—	
28	—		·01		·01		·01		·08		·02		—	
55	·01		—		—		—		·11		—		—	
56	—		—		·11		—		—		·03		—	
57	—		—		·02		·01		·06		·02		—	
59	—		—		·01		—		·04		·02		—	
60	—		—		—		·03		·10		·02		—	
	·01	·001	·02	·001	·21	·016	·12	·009	1·00	·077	·25	·019	·02	·001
49	—		—		—		·02		·08		·02		·04	
53	—		—		—		·02		·10		—		·03	
	·00	·00	·00	·00	·00	·00	·04	·02	·18	·090	·02	·010	·07	·035
Total of Means	—	·001	—	·065	—	·187	—	·752	—	1·771	—	·027	—	·859
Average for each day	·0001		·0065		·0187		·0752		·1771		·1027		·0859	

To face p. 6.

Or, since in the case of the Severn as shown on Plate 3, A = 1970·67, this becomes

$$C = 52{,}989I$$

and this factor was used in the subsequent work of conversion.

In order to facilitate this, tables were prepared such as shown for January, 1889, in Table III. In these were entered opposite their respective days the mean fall over the basin as obtained from the grouping method illustrated in Table II., this figure being in inches. Then, in the second column, was entered the same mean in cusecs obtained by multiplying the inches by 52,989 as indicated above.

SEVERN: TABLE III.

Second Tabulation of Results from Table II.

January, 1889.

Day.	Inches.	Cusecs.
1	·0133	705
2	·0010	53
3	·0005	27
4	·0004	21
5	·0001	5
6	·0014	74
7	·0126	668
8	·0804	4230
9	·2294	12160
10	·0110	583
11	·0047	249
12	·0084	445
13	·0039	207
14	·0000	0
15	·0022	117
16	·0264	1400
17	·0091	482
18	·0252	1335
19	·0415	2200
20	·0377	1997
21	·0029	154
22	·0033	175
23	·0026	138
24	·0014	74
25	·0001	5
26	·0065	345
27	·0187	990
28	·0752	3985
29	·1771	9380
30	·1027	5430
31	·0859	4550
Total for Month		52184
Mean for Month		1685

These tables also facilitated the calculation of the mean for each month. As will be observed, the work involved the preparation of 96 such tables as shown in Table II., and 96 as in Table III., with their accompanying calculations. The rainfall-curves were plotted from the figures shown in Column 2, Table III. This involved a considerable amount of work also, as about 3000 different figures had to be plotted on the curves for daily rainfall alone.

Rainfall Map.—The object in view was to make a map of the basin above Worcester, covering the eight years under consideration and showing lines of equal rainfall or isohyets. It was intended thus to draw in isohyets for 20, 25, 30, 35 inches a year, up to the highest annual rainfall occurring in the basin.

The method adopted was as follows : A table was prepared giving the total rainfall in each gauge for each year from 1882 to 1889. From this table rainfall maps were prepared for each year separately, thus :—

(*a*) A tracing was made of the basin from the $\frac{1}{4}$-inch Ordnance Map, showing the water-parting and all gauges, each gauge being represented by a $\frac{1}{4}$-inch diameter circle having its reference number written inside.

(*b*) Each year was then dealt with separately by placing a piece of plain tracing paper over the tracing referred to in (*a*), and drawing in the water-parting, and all gauge-circles representing gauges read in that particular year. In each circle was written the total rainfall for the year.

(*c*) On the tracing for each year as made in (*b*) the lines of equal rainfall were drawn in, thus providing eight maps.

(*d*) Commencing with 1882 and 1883, the maps for those years were placed together, and the mean between the isohyets showing the same rainfall drawn in on a third map ; *i.e.* taking, say, the 25-inch line on each map, a new line was drawn on the third map halfway between the two 25-inch lines. In this way a rainfall map was obtained for each pair of years, giving the mean for each two years.

(*e*) The maps of two-year means were then treated as in (*d*) by superposing, thus giving two four-year maps, and these were again combined to give the final eight-year map. This map is shown in Plate 3, Fig. 2, the areas of different rainfall being differently shaded.

It was considered necessary at this stage to devise some method by which the numerical calculations involved in the report might be checked.

To summarize the position. The daily rainfall figures were treated by the method of grouping described above, to obtain a figure for daily fall on whole basin. An average of the daily rainfall in each month was next made, giving the mean rate for each month. In a similar way mean rates of fall were worked out for six months, twelve months, and finally for the whole eight years. The rainfall in each case was worked out in cusecs. Obtained in this way the mean rate for the eight years 1882 to 1889 was 4807 cusecs.

Turning now to the rainfall map. This was prepared direct from the rainfall record sheets as described above, that is, the total yearly fall in each gauge as given on the sheets obtained from Dr. Mill was the figure worked from. Thus the map showed a result obtained by quite a different method from the calculations described above. It was thought, therefore, that if the mean rate of fall as obtained from the map agreed fairly with that from the grouping method, it would be a useful check.

The mean rainfall in cusecs for the eight years was therefore worked out from the map, Plate 3, Fig. 2, thus : taking, for example, the part of the basin between the isohyets of 45 and 50 inches, *i.e.* the strip marked J on the map, the area was measured by a planimeter and multiplied by the mean of 45 and 50, *i.e.* 47·5, thus giving the total fall for an average year on the area J. By treating the other areas inside the water-parting in a similar way, and adding the results together, a figure was obtained giving the mean fall on the whole basin for the period covered by the map, *i.e.* 1882 to 1889. This figure, reduced to cusecs, was 4764.

It will thus be seen that the two figures are practically identical, differing only by 1·09 per cent. This appears to me a highly satisfactory result, indicating as it does that both methods give a close approximation to the truth.

SEVERN: TABLE IV.

Table of Average Monthly Rainfalls and Discharges in Cubic Feet per Second.

Year.	1882.			1883.			1884.		
Month.	Rainfall.	Discharge.	Discharge as per cent. of Rainfall.	Rainfall.	Discharge.	Discharge as per cent. of Rainfall.	Rainfall.	Discharge.	Discharge as per cent. of Rainfall.
January	5890	3954	67·1	7800	4146	53·1	6375	2358	37·0
February	5480	3100	56·6	6770	—	—	5780	4264	73·7
March ...	3870	5360	138·5	2505	1734	69·2	4950	3100	62·6
April ...	6395	2194	34·3	1750	1320	75·5	2630	1654	62·8
May ...	3853	2222	57·7	2715	1076	39·6	2350	1354	57·6
June ..	8160	2326	28·5	5220	974	18·7	3842	580	15 1
July ...	6760	2472	36·5	4645	1104	23·8	5160	678	13·1
August ...	4820	1432	29·7	2315	1064	46·0	3475	500	14·4
September	4450	1646	37·0	9300	1720	18·5	3460	760	22·0
October ...	9100	3504	38·5	5915	3564	60·2	2820	1044	37·0
November	9990	5540	55·5	7335	4314	58·8	3665	1500	40·9
December	7480	5242	70·0	2955	3500	118·5	5540	3556	64·1
Mean	6354	3249	51 1	4935	2229	46·7	4170	1779	42·7

Year.	1885.			1886.			1887.		
January	4115	2046	49·8	7515	4300	57·2	4680	3794	81·0
February	6665	4594	68·9	2108	3268	155·0	1373	2142	156·0
March ...	2290	1800	78·6	5910	2484	42 0	2955	1444	48·8
April ...	4280	1534	35·8	3535	3354	94·8	2190	1134	51·8
May ...	4320	1302	30·1	11580	3714	32·1	3320	1072	33·2
June ...	5080	1074	21·2	2830	2100	74·2	2515	1074	42·7
July ...	1270	580	45·7	5350	812	15·2	2710	536	19·8
August ...	5270	968	18·4	2705	858	31·7	4190	658	15·7
September	8170	1574	19·3	5620	1200	21·3	4930	1120	22·7
October ...	9370	3454	36·8	8550	3188	37·3	4560	754	16·5
November	6358	3880	61·0	5050	2934	58·0	4230	2074	49·0
December	1990	3024	152·0	8920	5140	57·6	4520	3564	78·8
Mean	4932	2152	43·5	5806	2779	47·8	3514	1615	45·9

Year.	1888.			1889.		
January	1880	1520	80·9	1685	2034	121·0
February	1430	1044	72·9	3870	3148	81·3
March ...	4275	2116	49·5	4730	2804	59·2
April ...	3090	1846	59·7	8350	3926	47·0
May ...	1735	1052	60·5	5790	2620	45·2
June ...	4650	614	13·2	1160	974	84·0
July ...	9375	2346	25·0	4975	588	11·8
August ...	6550	1838	28·0	6425	936	14·6
September	1475	1714	116·0	4040	666	16·5
October ...	2480	742	30·0	6940	2314	33·3
November	9525	4522	47·5	2140	1974	92·2
December	4860	3322	68·3	3780	2684	71·0
Mean	4277	1889	44·1	4490	2056	45·8

Rainfall Curves.—For comparison with the discharge-curves the rainfall-curves were plotted in cusecs, showing the mean fall over the basin for each day, month, six-month period, and year.

As already stated, it was intended to plot curves for rainfall and discharge in the same units and on the same base; hence all the curves in Plate 1 and in Plate 2, Figs. 1, 2, 3, show both rainfall and discharge. This enables a comparison to be more easily made and brings out some points which might otherwise be missed.

Having arrived at this stage, we may now discuss the results obtained.

Discussion of Results.

General.—It will be observed from Plates 1 and 2 that in the discharge—as well as the rainfall-curves—irregularities tend to die out as the period over which the mean is taken is increased. For example, the daily curves, Plate 1, are extremely irregular, especially for the rainfall; whereas the yearly curves, in Plate 2, Fig. 3, are quite regular. There is naturally exhibited in all a distinct relation between rainfall and river-discharge, but the nature of this relation is quite different in the different curves.

It will now be well, instead of discussing the matter generally, to consider each part of the problem separately and the inferences we are justified in drawing.

Discharge Curves.—Considering the curves, Plate 1, showing daily discharge, it is interesting to examine the peaks due to sudden heavy rainfall. The shape of the curve for a rising river under certain conditions is quite distinct from that for a falling river; the former depending upon the nature of the rainfall, whether steady or irregular, its position in the basin and other factors; whereas the latter is governed only by the rate at which the water runs out of the river, assuming the rain to have ceased. The rising sides of the discharge-peaks thus show somewhat irregular sloping lines, convex outwards at their upper parts, concave outwards only near the bases of the peaks. The falling sides, on the other hand, show fairly smooth curves in every case where a sudden peak of rainfall is followed by a cessation of rain.

The height of the discharge-curve above its base must not be taken as indicating the height of the river, since the curve shows cubic feet of discharge per second, and this varies not directly with the height of the river, but with the mean velocity of the current and the sectional area of the stream at the time. Hence, we can hardly regard the curves of daily discharge as showing the true profile of flood-waves moving downstream, although, of course, each peak is coincident with a flood-wave in point of time.

It is also noticeable that the peaks on the discharge-curve which follow single isolated rainfall peaks appear to be bent slightly to the right in the curves, this effect being due to the convexity of the rising side and the concavity of the falling side, giving such peaks a somewhat tooth-like appearance. This appears to be the normal shape.

The concavity and regularity of the falling sides of the discharge peaks is more easily explained than the convexity of the rising sides. Taking the simple case of a channel filled with water which is allowed to flow out through an open end, it will be found that, when the rate of discharge is plotted against the time from commencing to discharge, a curve is obtained similar in appearance to that on the falling side of the peaks referred to. As pointed out above, this is not a curve showing fall of surface-level, but of discharge, which in any particular channel is governed by sectional area and mean velocity of flow; the latter depending not on depth alone but involving other factors, such as wetted perimeter.

Considering the rising side of a peak: When rain occurs in any part of the basin, however suddenly it may commence or cease, the water coming to the river cannot arrive suddenly in full volume and suddenly stop again like a flat-topped wave with vertical front and back. The fact that the rain falls over a considerable area would alone prevent this, as the water from the more distant parts of the rain area would arrive after that from the nearer parts. Thus, the profile of the flood-wave must have a sloping front and back. Assuming the rain to continue at a steady rate for long enough, then the wave must have a flat top; or, in other words, the river will rise until the discharge balances the inflow, and remain at this level of equilibrium as long as the rainfall continues steady. The natural shape, therefore, of the rising side of a discharge peak, since it must join up two horizontal lines representing the steady discharge of the river before the rain and after equilibrium has been established between inflow and outflow, is to leave the lower horizontal line by a curve concave outwards and to join the upper one by a similar curve facing the opposite way. The fact that the rainfall does not continue long enough nor steadily enough to give a flat top to the peaks does not appear to invalidate this reasoning.

Relation of Rainfall and River Discharge.—Considering first the curves such as Plate 1, showing the daily rainfall and discharge for 1882. The rainfall curve is irregular and non-continuous as was to be expected, since in fine weather it drops to the base-line, whereas this is never the case with the discharge-curve. It is clear also that the height of any point on the discharge-curve bears no relation to the height of the corresponding point which is vertically over it in the rainfall-curve, since the water flowing past the current meters at Worcester depended, not on the rain falling at the same moment, but on the rain which had fallen at some time before.

It will be noticed, on comparing the peaks on the two curves, that there is a fairly definite time-interval between the rainfall and discharge peaks. This appears to be about two days. It is thus clear that the level of the river on any particular day is governed chiefly by the rainfall in the basin about two days before. Since this time-lag depends on the time taken for the water falling in the basin to reach Worcester (or, in other words, on the distance travelled), it could only be of uniform value if the rainfall always had the same distribution, which is not the case.

The actual value of lag will depend upon the length of path the water has to travel and such factors as affect its rate of travel; as slope of river-bed, gradients in basin, and amount of rainfall.

Relative Height of Peaks.—The proportion of the rainfall which reaches the river is variable, as will be shown later, and it depends to a great extent on the state of the ground as regards saturation, especially when short periods are considered, such as days or months. If the ground is dry it soaks up the rain, if wet it permits it to run off into the river. If now we examine the relation between the heights of the rainfall and discharge peaks, it will be seen that, when there has been a spell of dry weather the effect of a rainfall peak on the discharge is much less than during wet weather. For example, looking at Plate 1, a spell of fine weather began on July 27, 1882, and lasted till August 11. During this time the river fell steadily, the slight rainfall on Angust 2 being almost negligible in its effect. Rain commenced again on August 11, and was practically continuous until September 6, but, in spite of this, the first discharge-peak after rain began was on August 25. On the other hand, compare the period July 1 to 27 when rain was fairly continuous: here each rainfall-peak has its corresponding discharge-peak. This effect of percolation tends to become of less importance the longer the period considered, and for yearly periods has little importance in the present connection.

Rainfall lost by Evaporation, Percolation, etc.—Referring to Table V., it will be noticed that the percentage of total rain which appeared in the discharge was consistently less in summer than in winter, even when the actual amount of rain falling was greater in summer. For example, take the year 1882, in which the mean rate of rainfall for the six months April to September inclusive was 5739 cusecs; the percentage of this appearing as river discharge was 35·75. In the year 1887 the rainfall for the months October to March inclusive was only 3483 cusecs, while of this as much as 66·8 per cent. appeared in the discharge of the river.

SEVERN: TABLE V.

Table of Average Rainfall and Discharge in Winter and Summer in Cubic Feet per Second.

Winter months were taken to be October, November, December, January, February, March; Summer months were taken to be April, May, June, July, August, September.

Year.	Rainfall.	Discharge.	Season.	Discharge as per cent. of Rainfall.
				%
	5080	4138	Winter	81·4
1882	5739	2049	Summer	35·75
	7274	4033	Winter	55·4
1883	4324	1209	Summer	27·96
	5552	3517	Winter	63·34
1884	3486	921	Summer	26·42
	4182	2423	Winter	57·93
1885	4732	1172	Summer	24·76
	5542	3402	Winter	61·38
1886	3603	2006	Summer	55·67
	5255	3107	Winter	59·1
1887	3309	932	Summer	28·1
	3483	2329	Winter	66·8
1888	4479	1568	Summer	35·0
	4525	3674	Winter	81·1
1889	5140	1618	Summer	31·5
	4287	1162	Winter	27·1

It is thus obvious that, although percolation must be an important factor in determining the loss, it is not the governing factor. It seems, therefore, that we must look to evaporation, and perhaps the growth of vegetation in the warmer months, to explain the relatively small proportion of the rainfall which reaches the river.

The curve Plate 2, Fig. 4, shows the fairly regular way in which the loss of water varies in summer and winter.

It is of importance to consider the possibility of establishing a general relationship between rainfall and run-off, and this matter has received careful consideration. When we keep in mind the factors which determine the loss, we find these are numerous. The chief are as follows :—

1. Nature of basin as regards porosity, as affecting percolation and absorption.
2. Degree of saturation of soil with water, as affecting percolation and absorption.
3. Prevailing gradients and shape of basin as affecting time available for percolation, absorption, evaporation, etc.
4. Temperature of air and ground as affecting evaporation and storage, especially when it is below freezing point.

5. Nature of winds.
6. Relation of actual surface to projected area, *i.e.* degree of roughness of surface exposed for evaporation.
7. Effects of vegetation in impeding evaporation, absorbing water during rapid growth, and in other ways.
8. Whether cultivated ground or not.
9. Storage capacity in lakes, swamps, etc., and gravel or porous beds underground.
10. Nature of precipitation; *i.e.* whether rain or snow.

Numbers 1, 3, 6 and 9 are fixed for any basin. Number 2 depends on amount of rainfall. Numbers 4, 5, 7 and 10 are more or less seasonal but uncertain factors. It would thus appear that it is useless to expect a strict and calculable relation to exist between rainfall and run-off, since we cannot tell to what extent it will be influenced by the uncertain variable factors. Obviously, the longer the period considered, the more probability there is of finding a relationship which is approximately true for all such periods. It is, however, certain that the seasonal variations in the ratio make it necessary to consider one year as the absolute minimum period; since that is the shortest time which includes a complete cycle of the seasons. Even then we find a variation of from 42·6 to 51·2 in the percentage of rainfall which appears as discharge; this is shown in Table VI.

SEVERN: TABLE VI.

TABLE OF AVERAGE YEARLY RAINFALLS AND DISCHARGES IN CUBIC FEET PER SECOND.

Year.	Rainfall cusecs.	Discharge cusecs.	Discharge as per cent. of Rainfall.	Loss due to absorption, etc., cusecs.
1882	6354	3249	51·2	3105
1883	4935	2229	45·2	2706
1884	4170	1779	42·6	2391
1885	4932	2152	43·6	2780
1886	5806	2779	47·9	3027
1887	3514	1615	46·0	1999
1888	4277	1889	44·2	2388
1889	4490	2056	45·6	2434
Mean	4807	2218	46·2	2604

Mean yearly fall in basin as found from tables = 4807 cubic feet per second.

The variable factors affecting the amount of loss appear to be, to some extent, functions of the rainfall. For example, the degree of saturation of the soil depends on the rainfall; the loss by evaporation bears some relation to the amount of rain, since when it is raining there can be little evaporation going on; even the growth of vegetation is itself more or less governed by the amount of rainfall. Arguing along these lines, it seemed probable that if the total loss were plotted against the total rainfall it might bring out some relation, since all the above factors appear to indicate that the greater the rainfall, the less will be the loss by evaporation, etc. Such a curve was plotted, and the result for the yearly figures is shown in Fig. 1. It will be seen that it gives a curiously smooth curve. It is questionable how far this relation will hold good beyond the eight years considered; but for this period the curve in Fig. 1 certainly does give with great accuracy the relation between rainfall and loss for any year.

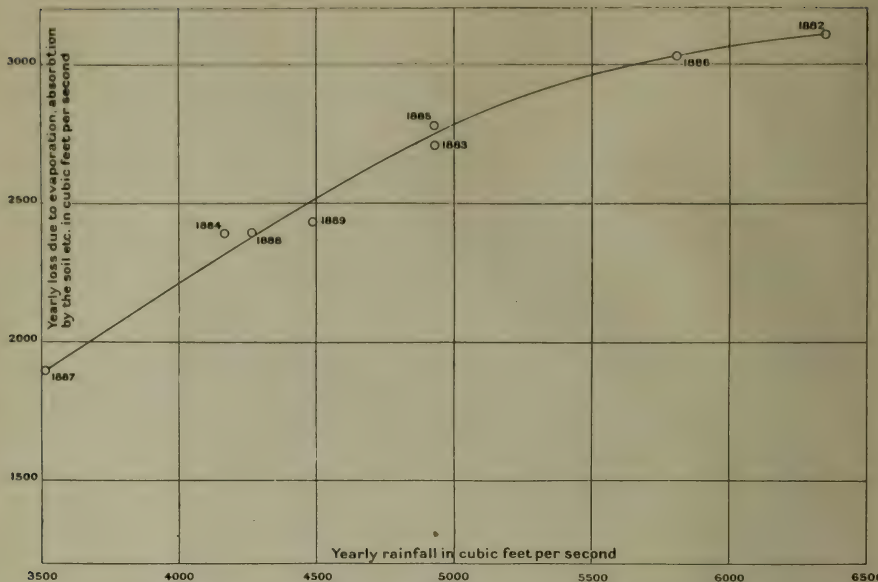


FIG. 1.—CURVE SHOWING RELATION BETWEEN YEARLY LOSS DUE TO EVAPORATION, ABSORPTION BY THE SOIL, ETC.; AND THE YEARLY RAINFALL FOR THE YEARS 1882 TO 1889 INCLUSIVE.

SEVERN: TABLE VII.

TABLE SHOWING FIGURES OBTAINED FROM MAP OF AVERAGE RAINFALL.

Area.	Area in square miles.	Mean rainfall in inches.	Rainfall in cubic feet per second.
A	31·40	26·25	60·70
B	49·75	26·35	96·30
C	340·80	26·875	722·00
D	545·50	28·25	1134·00
E	165·30	30·75	373·50
F	63·50	31·875	149·00
G	133·00	33·625	329·00
H	245·20	37·50	678·00
I	197·00	42·50	616·00
J	135·30	47·50	476·00
K	21·15	50·00	77·80
L	15·52	30·00	34·35
M	3·20	32·25	7·60
	Total ...	... ...	4754·25

Mean yearly fall in basin as found from map = 4754·25 cubic feet per second

I tried plotting similar figures for the Hudson, Genese, amd Croton rivers, but found they only gave points scattered irregularly over the paper and no semblance of a curve. The data used were taken from Bulletin 85, New York State Museum, on the hydrology of the State of New York; I do not know what degree of accuracy

can be relied on in the figures used, especially those for rainfall. It may be, however, that these rivers were too much affected by frost, or that a large proportion of the precipitation in their basins was in the form of snow; in which case one could not expect any regular curve to result. On the other hand, it may be that it is only by coincidence the Severn figures give a smooth curve; but I do not hold this view myself. When I saw that there was an indication of some regular curve, I sent a copy of the curve produced in Fig. 1 to Mr. MacKenzie, and he plotted the figures for the Exe in a similar way, with the result that for the basin both above Brampford Speke and above Exeter he obtained curves almost identical with that shown in Fig. 1. It seems therefore certain that some regular relationship is indicated in all these cases. Whether Fig. 1 represents a definite relationship between the rainfall and the loss or not, it is, I think, the form one would expect to find such a relationship taking, since, as already mentioned, all the factors except frost tend towards a greater percentage run-off with heavy than with lighter rainfall.

The curve Plate 2, Fig. 4, is of interest as showing graphically the way in which the loss by percolation, evaporation, etc., varies month by month. Generally speaking, the percentage of rainfall lost is higher in the summer than in the winter. The dotted line is drawn in to show this more clearly; it is simply an average drawn through the actual curve to smooth down the irregularities, and it is curious to note how regular the variation is between summer and winter.

THE MEASUREMENTS OF DISCHARGES.

By N. F. MACKENZIE, M.Inst.C.E.

When considering methods of measuring the discharge of the rivers under investigation, it was evident at the outset that the funds available would not admit of the construction of any form of dam or weir. Failing the method of gauging discharges from the depth on a weir crest, other possible methods were discussed.

The discharge of any channel is given by the area of its cross-section multiplied by its mean velocity. The area of the section is got by direct measurement, and the problem that presents itself is therefore the determination of the mean velocity. This may be arrived at in various ways, of which the most usual are—

From velocity-rod observations.
From current-meter observations.
From surface velocities.
From the slope of the water-surface.
From velocities at different depths got by sub-surface floats.

The velocity of a floating weighted rod reaching from the surface nearly to the bed, is found, by experiment, to be for all practical purposes the mean velocity of the vertical plane in which it moves, and velocity-rods are almost universally used in India for the measurement of canal discharges. Unfortunately, river-beds are, as a rule, too irregular to admit of their use.

Under favourable conditions, the current meter may be expected to give good results, but the men responsible for the observations had no previous experience in its use; and, apart from this, the time occupied by current-meter observations is far greater than they could devote to the work.

It was therefore decided that, whenever possible, the mean velocity should be calculated from observed surface velocities, using a coefficient or reduction multiplier. The coefficient varies with the *rugosity* of the channel, a term which includes all obstructions or irregularities which interfere with the free flow, and it also varies with the hydraulic radius of the channel. The coefficient is therefore

not constant even in channels of the same rugosity, nor in the same channel for different gauge-readings.

In selecting a coefficient for reducing surface velocity to a mean velocity accurate data are fortunately available. For many years Indian irrigation engineers have experimented on the relation between surface and mean velocities, and on these experiments are based tables of coefficients which are accepted as correct for all purposes of discharge calculation.* Indeed, some irrigation engineers consider that surface-velocity observations give results even more reliable than those obtained from velocity-rods.

The difficulty in the method lies in the proper determination of the rugosity of the channel. This is a matter of expert knowledge, but is comparatively easy for any one who has had experience in this method of measuring discharges.

Measurement of the surface velocity presents no difficulty. The river is divided into longitudinal sections, and floats are run over a measured distance, usually 50 or 100 feet, the time of passage being noted. The mean of several runs is taken for each section, and the length of run divided by the time of passage gives the surface velocity of the section.

Having obtained a series of measured discharges for various gauge-readings, these are plotted on squared paper and through the plotted points a discharge curve is drawn from which the discharge for any given gauge-reading is obtained.

The discharge site should be situated in a reach of the river as straight and uniform as possible, and a gauge is erected at the selected site. The gauge should be read at least once a day, and if possible hourly readings should be recorded during floods.

To obtain the area of the mean cross-section of the stream over the discharge site several cross-sections are measured some twenty or thirty feet apart and the mean of these is taken as the mean cross-section. A rope is stretched across the stream in the line of the proposed section and the positions of the soundings are marked on the rope; 5-feet intervals are convenient for rivers of from 50 to 150 feet width. The soundings are taken from a boat rowed or towed into position opposite the marks. When the depth does not exceed 10 feet the soundings are taken with a sounding-rod marked in feet and decimals, or in feet and inches, and the rod should be terminated by a disc so that it may not sink into the bed of the stream. When the depth exceeds 10 feet a sounding-line is used. The soundings are taken preferably when the river is low and the gauge-reading is noted at the time of measurement. The profile of the cross-section should be continued on either side beyond the water edge by levelling or by measurement of slopes and distances, so that when the section is plotted on paper the stream area for any given gauge-reading may be determined.

After the cross-section of a river has been plotted it should be checked from time to time to see whether it has altered. Rivers contained in clean-cut channels seldom alter very much, but rivers in beds of gravel or sand and especially if subject to violent floods may alter considerably. On the Exe the cross-sections were measured in 1906 and in 1907; these were checked in 1911, and it was found that there had been no alteration of any practical importance.

For convenience in recording velocity observations printed forms were supplied to the observers, and these contained certain instructions shown by experience to be worth attention. These were as follows:—

"It is useless to take observations in wind."

"The same observer should note the moment when the float enters and leaves the measured length."

* See Appendix.

"The duration of the run should be noted to a fifth of a second."

"If any interruption occurs, such as collision of the float with an obstacle, or the catching of the float in an eddy, the observation should be rejected."

"All uninterrupted runs should be recorded, even though they differ considerably in duration."

"Five uninterrupted runs for each section constitute a complete observation."

THE EXE.

Two discharge sites were established on the Exe, one at Exeter quay above the influence of tidal water, and the other close to Brampford Speke railway station, six miles above Exeter (see map, Plate 9). Cast-iron gauges, divided into feet and inches, were erected at the discharge sites, and it was arranged that these should be read daily, at Exeter by men in the employ of the Exeter City Council, and at Brampford Speke by the stationmaster, Mr. A. Tucker.

At Brampford Speke an additional gauge was erected 1000 feet upstream of the discharge site gauge, and its zero was connected to the discharge site gauge by levelling. It was hoped that readings on the two gauges would afford useful information regarding the surface slope of the river during floods. These flood-readings were of great help, as will be explained later, in determining the discharge curve for gauges for which surface velocity measurements were not available.

Another gauge was erected at Exebridge 22½ miles above Brampford Speke, though no discharge site was established at this point. The object of this gauge was to give information as to the time occupied by the crest of a flood in passing down the valley. The gauge-readings were recorded by Mr. Ballinger, and subsequently by Mr. Wallis, by permission of Mr. T. F. Tracy, proprietor of the Exe Valley Fisheries.

It is not necessary that the gauge zeros should be at the level of the river-bed, though it is desirable to fix the zero as low as possible to avoid minus readings in dry weather.

For the Brampford Speke gauge there were eight measured discharges for various gauges. These were plotted; and one or two discharges were interpolated by calculation, using Bazin's formula, which is less complicated than Kutter's, and which is reliable except for very flat surface-slopes such as are found on the Medway. On the curve are indicated the actual positions of the eight measured discharges, and six of the eight lie exactly on the curve, while two discharges lie outside the curve. These two abnormal discharges are very instructive.

The lower discharge was for a gauge of 1 foot 6¾ inches, and gives a volume of 363 cusecs. In the record the observer (Mr. Beckit) notes as follows: "In the right-hand section many small twigs of trees hung into the water, and this may have affected the floats, though this was not visibly the case." In this section the average timing of the floats over a run of 100 feet was 31·8 seconds. Assuming that the twigs did interfere with the floats, and that the timing ought to have been about 30 seconds, this adds 13 cusecs on to the discharge, making it 375 cusecs, which exactly comes on to the curve.

The second abnormal discharge was for a gauge of 2 feet. The observer (Dr. Strahan) notes that in one of the sections the floats had to be run further out from the bank than usual, as some overhanging bushes would otherwise have interfered with them. This means that in that particular section the surface velocity, and therfore the discharge, was somewhat too great. This again coincides with what is shown by the discharge-curve.

These two abnormal discharges indicate—

1. The value of a graphic curve rather than a table of figures. The curve shows at once where a measured discharge does not agree with the other measured discharges, and this might easily be overlooked in a table of figures.

2. The extreme importance of an observer noting any detail, however apparently trivial, which might affect his observations.

The notes by Dr. Strahan and Mr. Beckit show clearly that the curve is correct, and that their observations were affected by influences which, small in themselves, are appreciable when plotted on squared paper. But for these notes, the causes of the abnormal discharges would have remained uncertain.

During some of the floods, readings on both gauges at Brampford Speke were recorded and from the surface slope thus arrived at, the coefficient of rugosity of the river at this point was computed, the required discharges being got from actual measurement.

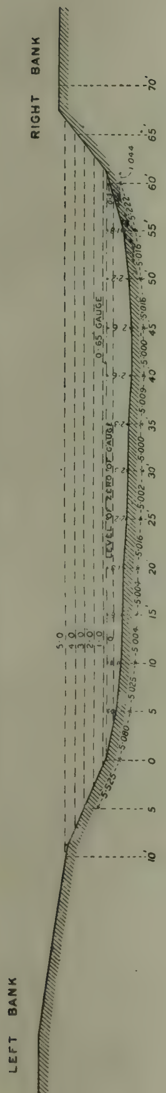
The coefficient of rugosity depends on the actual condition of the channel, and as this does not appreciably vary with the depth of the river, it follows that the value of the coefficient should be fairly constant whatever the discharge, on the assumption that the recorded discharge-observations are correct. Working out the value of the coefficient for five separate measurements; three give a value of 0·030; one, a value of 0·0305; and one a value of 0·031; and the higher values of the coefficient correspond to the higher gauge-readings. It must be noted that the discharge is inversely proportionate to the value of the coefficient, other conditions being equal. These computed results are satisfactory. At normal gauges the river flows in a self-formed channel with smooth bed and side slopes; at flood gauges part of the channel has grass and other undergrowth, and the increased friction results in a less favourable coefficient of rugosity. The values of the coefficient correspond to Kutter's classification of a river in good *régime*, and this theoretical description is borne out by the clean-cut regular section of the Exe shown on the diagram (Fig. 2).

From the value of the coefficient were worked out, by the surface slope method, discharges of the Exe for gauges higher than those for which there are actual discharge measurements; and the discharge curve plotted is based on actual measurements up to 4·3 feet, and on surface slope calculations up to 9·0 feet (Fig. 3). The curve differs slightly from actuals at 4½ and 5-feet gauges; the explanation probably is that the 4·3-feet measured discharge was slightly too great, and this affects the 5·0-feet calculation based on the 4·3-feet measurement. With these exceptions the curve agrees wonderfully well with actuals, and it forms the basis of the discharge records.

The computed portion of the curve is not often required; during the period January 1, 1907 to March 31, 1912, the gauge-reading was higher than 4·3 feet on some sixty occasions only.

At the Exeter quay gauge on the Exe the discharges actually measured were sufficient to furnish a discharge curve for all gauge-readings up to 4½ feet, but the river at this point occasionally rises higher than this. During the 5¼ years for which there are records, there is one gauge-reading of 6 feet, one of 5 feet 9 inches, and four or five round about 5½ feet. To complete the discharge curve up to a gauge of 6 feet a measured discharge for a gauge of 5½ feet was very desirable, but there were practical difficulties in the way. Floods of this magnitude are of rare occurrence, and fall so rapidly that, except for an observer actually on the spot, there was little chance of hitting off a maximum flood. It was only in the fifth year of the investigation that the curve was completed by actual measurement up to a gauge of 4½ feet. It had been agreed to close the observations in March, 1912, without waiting for more measured discharges, and in order to make the most of

CROSS SECTIONS OF THE RIVER EXE.

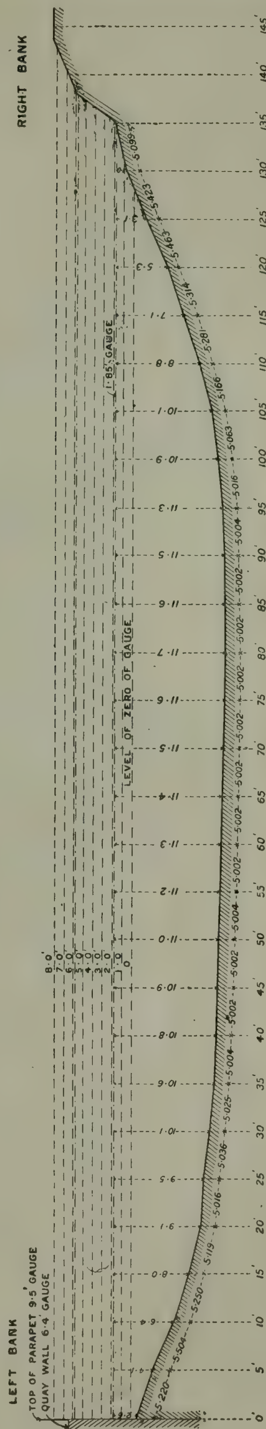


MEAN CROSS SECTION OF RIVER EXE AT BRAMPFORD SPEKE.

TAKEN 8.8.07 GAUGE READING 0·65

SCALE 20 FT. TO 1 INCH

DRAWN FROM SOUNDINGS TAKEN BY MESSRS STRAHAN & BECKIT.



MEAN CROSS SECTION OF RIVER EXE AT EXETER.

TAKEN 4.9.06 GAUGE READING 1·85.

SCALE 20 FT. TO 1 INCH.

DRAWN FROM SOUNDINGS TAKEN BY MESSRS STRAHAN, HERBERTSON, ELTON, & BECKIT.

NOTE. THE MEAN SECTIONS ARE IN BOTH CASES DEDUCED FROM SIX SECTIONS, MEASURED AT INTERVALS OF 20 FEET LONGITUDINALLY.

FIG. 2.

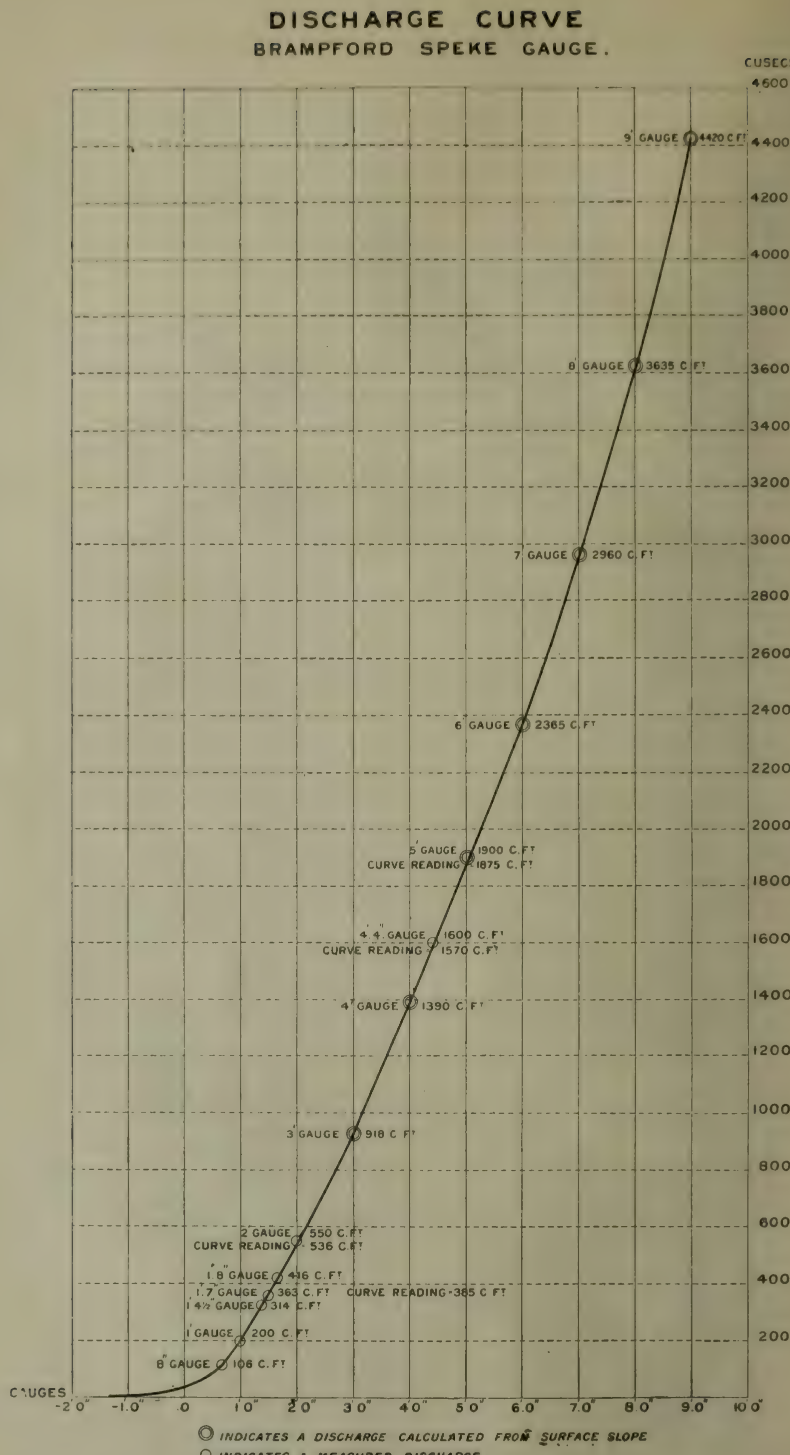

DISCHARGE CURVE
BRAMPFORD SPEKE GAUGE.
CUSECS
4600
4400
4200
4000
3800
3600
3400
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
9' GAUGE 4420 C FT
8' GAUGE 3635 C FT
7' GAUGE 2960 C FT
6' GAUGE 2365 C FT
5' GAUGE 1900 C FT
CURVE READING 1875 C FT
4' 4" GAUGE 1600 C FT
CURVE READING 1570 C FT
4' GAUGE 1390 C FT
3' GAUGE 918 C FT
2' GAUGE 550 C FT
CURVE READING 536 C FT
1' 8" GAUGE 416 C FT
1' 7" GAUGE 363 C FT
CURVE READING 385 C FT
1' 4½" GAUGE 314 C FT
1' GAUGE 200 C FT
8" GAUGE 106 C FT
GAUGES
-2 0"
-1.0"
.0
1 0"
2 0"
3 0"
4 0"
5 0"
6.0"
7.0"
8.0"
9.0"
10 0"
◎ INDICATES A DISCHARGE CALCULATED FROM SURFACE SLOPE
○ INDICATES A MEASURED DISCHARGE

FIG. 3.

the data already accumulated, it was decided to compute the discharges for gauges higher than $4\frac{1}{2}$ feet. The method of computation requires explanation.

Whatever formula be used for calculation, the unknown factor is the slope of the water surface. From the measured discharges the surface slopes for different gauges were computed by Bazin's formula, and the results are shown in Table VIII. :—

TABLE VIII.

$$D = CA\sqrt{RS} \text{ (Bazin).}$$

Gauge.	Area (A).	Wetted perimeter (WP).	Hydraulic radius $\left(R = \frac{A}{WP}\right)$	C.	$CA\sqrt{R}$	Slope in unit length (S).	D.
2·0	1226	138·0	8·88	89·5	326979	·000001	320
2·25	1260	138·6	9·09	89·8	341137	·000002	490
2·5	1294	139·2	9·29	90·1	355359	·000004	710
2·75	1328	139·8	9·40	90·4	369828	·000007	960
3·0	1362	140·5	9·69	90·6	384120	·000010	1245
3·25	1396	141·1	9·89	90·9	399069	·000015	1550
3·5	1430	141·7	10·09	91·2	414263	·000020	1925
3·75	1464	142·3	10·28	91·5	429495	·000029	2310
4·0	1498	143·0	10·47	91·8	444967	·000040	2750
4·25	1532	143·6	10·66	92·0	460183	·000049	3195
4·5	1566	144·2	10·86	92·3	476330	·000060	3675
5·0	1634	145·5	11·23	92·7	507600	[*·000080	4540
5·5	1702	146·7	11·60	93·0	539103	·000100	5390
6·0	1770	148·0	11·90	93·3	569677	·000120	6240*]

It will be seen that from gauges of $3\frac{1}{2}$ feet to $4\frac{1}{2}$ feet the slopes got from actual measurement increase in arithmetical progression as nearly as possible, and it has been assumed that this rate of increase holds for higher gauges also. On this assumption the discharges up to a 6-foot gauge have been calculated, and the discharge curve (Fig. 4) has been plotted.

The assumed values for the higher surface slopes may be incorrect, but there is evidence to show that the error cannot be very great. The discharge curve from 3 feet 9 inch gauge to 4 feet 3 inch gauge is a straight line, and the computed portion of the curve is a continuation of this line.

The error, if any, probably lies in the discharges being too small. Were they too large, the correct curve above 4 feet 6 inch gauge would be a reverse curve which indicates a river where a considerable increase in depth causes a comparatively small increase in sectional area, for example, a river in a narrow gorge, and this condition does not apply to the Exe. If the surface slope for a 6-feet gauge be increased by 33 per cent., and the slopes for the 5-feet and $5\frac{1}{2}$-feet gauges be increased proportionately, then the resulting discharge for the 6-feet gauge is 10 per cent. higher than that shown by the curve, the $5\frac{1}{2}$-feet discharge is 5 per cent. higher, and the 5-feet discharge is less than 3 per cent. higher. During the $5\frac{1}{4}$ years for which there are records, there are but four gauges of $5\frac{1}{2}$ feet and upwards, and twenty-one of from $4\frac{1}{2}$ feet to $5\frac{1}{2}$ feet, so that the effect of any possible error in the assumed curve is practically negligible when considering total annual, or even total monthly volumes. The final result seems to justify the decision to complete the work instead of waiting for an opportunity of measuring an exceptionally high flood.

The measurements on which the curve from $3\frac{1}{2}$ feet to $4\frac{1}{2}$ feet is based, were

* These figures are estimated, all others are from actual measurements.

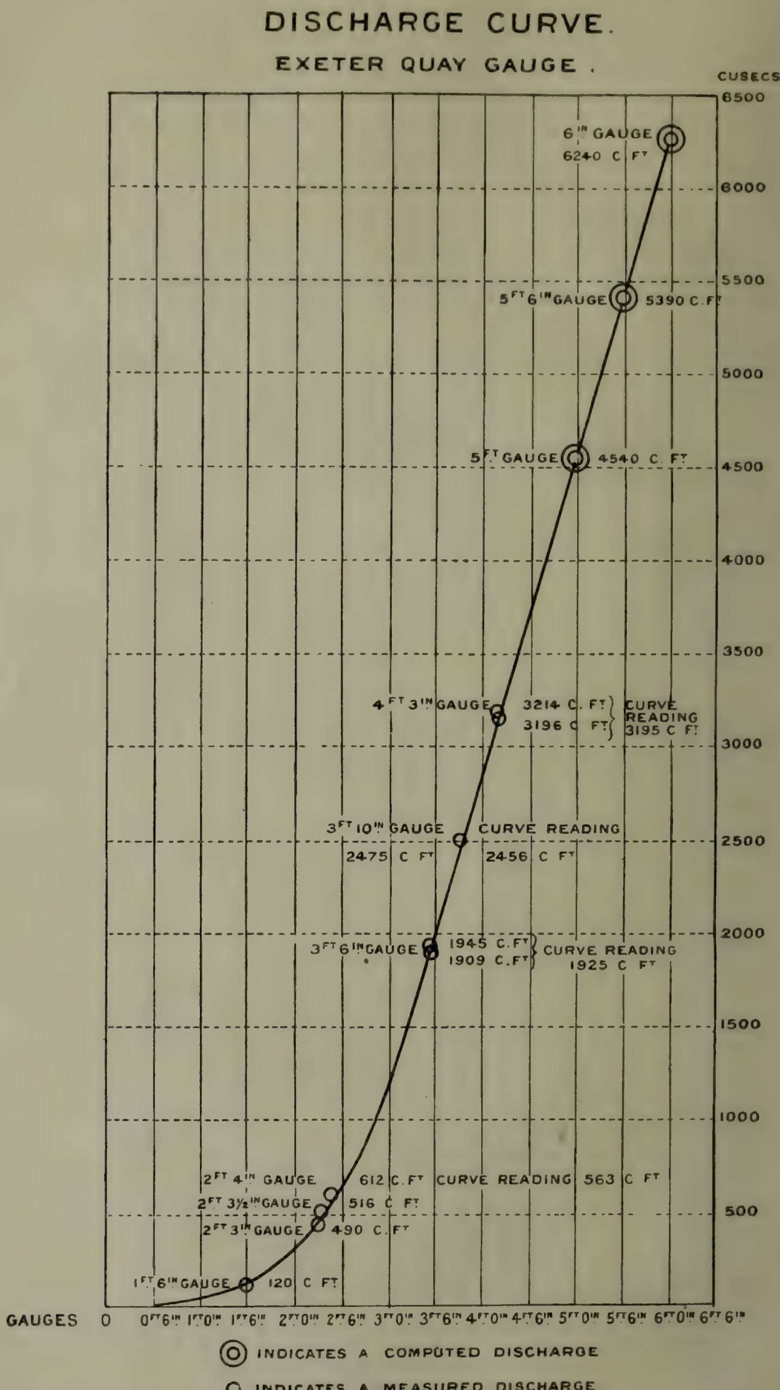

DISCHARGE CURVE.
EXETER QUAY GAUGE.
CUSECS
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
6IN GAUGE 6240 C FT
5FT 6IN GAUGE 5390 C.FT
5FT GAUGE 4540 C. FT
4FT 3IN GAUGE 3214 C. FT 3196 C FT CURVE READING 3195 C FT
3FT 10IN GAUGE 2475 C FT CURVE READING 2456 C FT
3FT 6IN GAUGE 1945 C.FT 1909 C.FT CURVE READING 1925 C FT
2FT 4IN GAUGE 612 C.FT CURVE READING 563 C FT
2FT 3½IN GAUGE 516 C FT
2FT 3IN GAUGE 490 C.FT
1FT 6IN GAUGE 120 C FT
GAUGES 0 0FT 6IN 1FT 0IN 1FT 6IN 2FT 0IN 2FT 6IN 3FT 0IN 3FT 6IN 4FT 0IN 4FT 6IN 5FT 0IN 5FT 6IN 6FT 0IN 6FT 6IN
INDICATES A COMPUTED DISCHARGE
INDICATES A MEASURED DISCHARGE

FIG. 4.

carried out on three days in January, 1912, during a well-sustained flood, and bring out two points of interest which may be mentioned.

On the first day two discharges were measured under very favourable conditions; the gauge-reading was perfectly steady and the weather was dead calm. The width of the river was divided into three sections, and surface velocities were measured in each section; the timings in each case were remarkably regular, differing only by decimals of a second. In the first discharge the surface velocity in the left section was distinctly higher than the mid-stream velocity, the difference being about 0·25 foot per second. In the second discharge the velocities in these two sections were exactly the same. Working out the discharges it was found that they differed by 0·5 per cent. in a volume of about 3000 cusecs. This illustrates the well-known fact that variations of surface velocity in one or more sections of a river do not necessarily indicate variations in the total volume. The difference in the two discharges was probably due to errors of observation.

On the following day a discharge was measured in a dead calm; later on the gauge was the same as before, but there was a light air blowing up-stream, just sufficient to ripple the surface. A second discharge was measured which worked out to 10 per cent. less than the first, which illustrates the great defect of the surface-float method of measuring discharges. It is useless for reliable results to take observations in a wind.

During floods in the Exe, gauge-readings at three points were taken at intervals of one hour, the object being to trace the passage of the flood-wave down the river. Some of these records have been plotted, and they are interesting. When the flood reaches its maximum at night, the exact time is generally lost; therefore those floods only which leave little doubt as to the actual time of high water have been considered. The gauges are situated at Exebridge: at Brampford Speke, 22½ miles below Exebridge; and at Exeter quay, 6 miles below Brampford Speke. The diagrams represent gauge-readings only, and not discharges, and as the gauge-zeros are not connected in any way, the gauge-readings are not necessarily plotted from the same datum line.

These records are not sufficiently numerous to give any accurate idea of the behaviour of the flood-wave; but one or two points of interest may be noted.

What is very apparent on all the diagrams is the rapidity with which the Exe rises and falls.

In the diagram Fig. 5, No. 1, we have the record of a moderate flood of 1566 cusecs at Brampford Speke. The river rose 36 inches at Exebridge in 24 hours, and fell 14 inches in 4 hours. At Brampford Speke the rise was 55 inches in 28 hours, and the fall was 25 inches in 8 hours. At Exeter the rise and fall are similarly well marked, though less abrupt than in the higher reaches. High flood is noted at Exebridge at 8 a.m., at Brampford Speke at 10 a.m., and at Exeter at 2 p.m. The Exebridge time is doubtful, the maximum gauge, no doubt, was at 8 a.m., but probably the water-level was only slightly lower for some hours previous.

Fig. 5, No. 2, shows a flood of the same magnitude as Fig. 4, No. 1, and the flood-crest took 5½ hours to traverse the 22½ miles between the gauges.

Fig. 5, No. 3, is peculiar; it shows a high flood at Exeter and at Brampford Speke, 2414 cusecs at the latter point. In the upper portion of the valley there was no flood; the river at Exebridge was quite normal. The Culm and Creedy were also in high flood at the same time.

Fig. 5, No. 4 is the converse of Fig. 4, No. 3. An exceptionally high flood occurred at Exebridge on October 16. The river rose 79 inches in 24 hours. This was due to heavy rainfall, amounting to 4·41 inches during the first fourteen days of the month. At Brampford Speke the river rose 69 inches in 25 hours, and these sudden

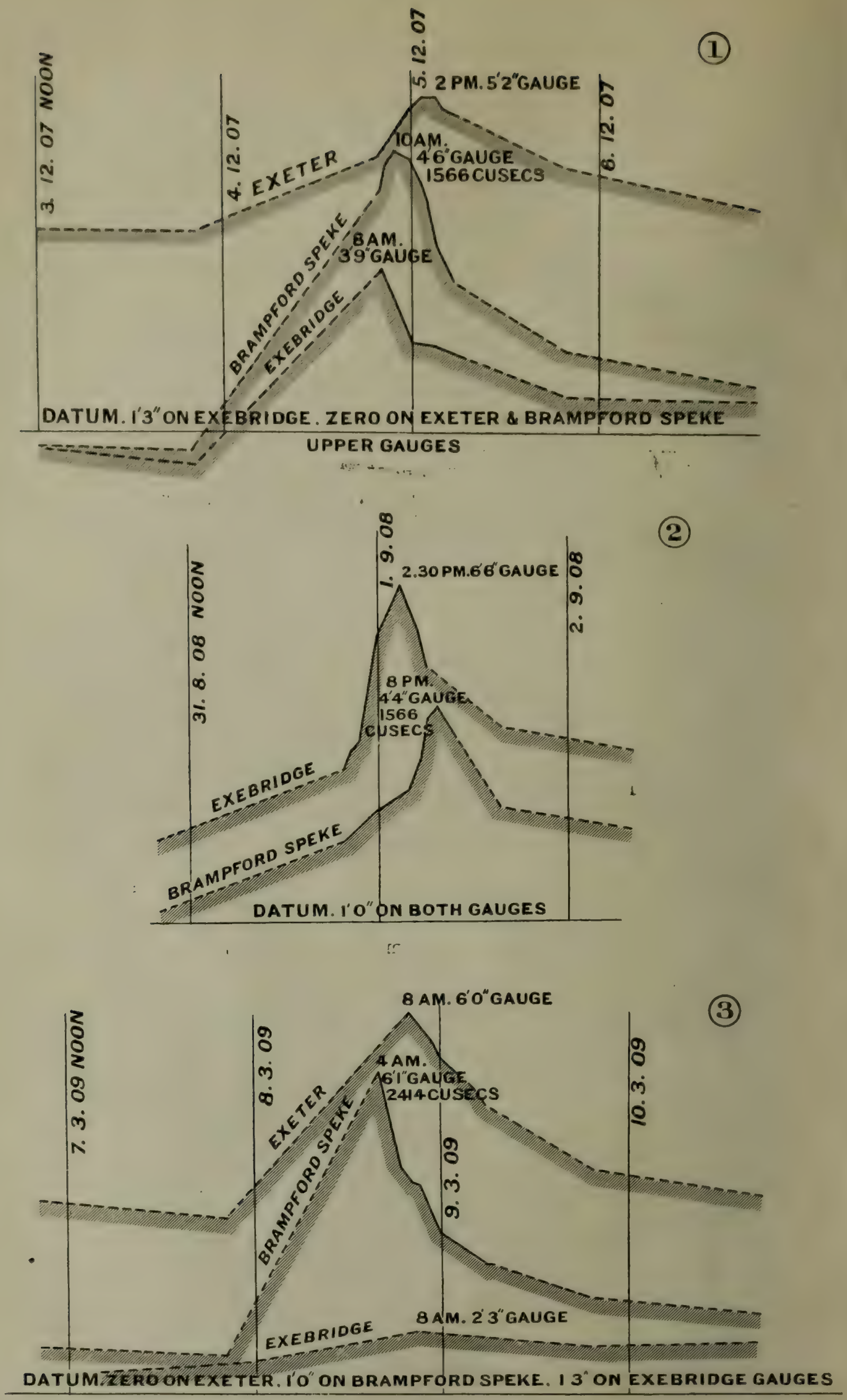


FIG. 5.—FLOOD GAUGES ON THE RIVER EXE.

Horizontal scale, 1 inch = 24 hours. Vertical scale, 1 inch = 3 feet.

NOTE.—Dotted lines are plotted from daily gauge readings, and full lines from hourly readings.

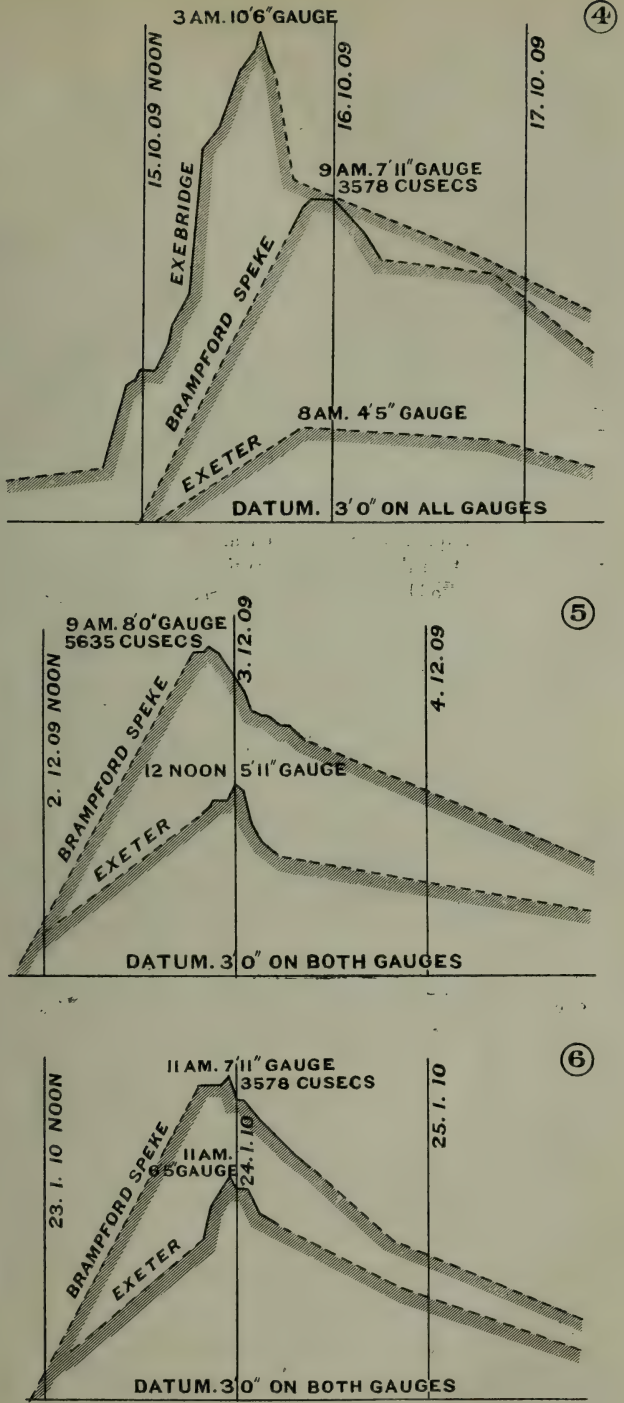


FIG. 5.—FLOOD GAUGES ON THE RIVER EXE.

Horizontal scale, 1 inch = 24 hours. Vertical scale, 1 inch = 3 feet.

NOTE.—Dotted lines are plotted from daily gauge readings, and full lines from hourly readings.

rises were followed by sudden falls, particularly at Exebridge. Although the flood in the upper reaches was very intense, it was of short duration, and the effect on the Exeter gauge was a rise of 22 inches only, and the gauge-reader there did not record hourly readings. The maximum gauge at Exeter was 4 feet 5 inches, and a much smaller flood in the upper reaches, but of longer duration, raises the Exeter gauge to 5 feet and over.

Fig. 5, Nos. 5 and 6 show two very high floods at Exeter and at Brampford Speke. In Fig. 5, No. 5, high water at Exeter is 3 hours later than at Brampford Speke, and in Fig. 5, No. 6 the interval is 3½ hours. In Fig. 5, No. 6 there is a sudden rise of 1 inch at Brampford Speke at 11 a.m., which coincides with the time of high water at Exeter. This was probably caused by a wave passing down the river when the gauge was read; by the time it arrived at Exeter the river was falling, and its effect was to check the fall of the river, as shown on the diagram.

The general conclusion to be drawn from the diagrams is that the flood takes 5 or 6 hours to pass from Exebridge to Brampford Speke, and 3½ hours more to reach Exeter, but these figures are very rough.

The following table traces the passage of the Exe floods down the valley. It is not very complete, as it frequently happens that moderately high floods in the upper reaches have so little effect on the Exeter gauge that hourly gauge-readings are not recorded. Again, where a flood lasts for two days at Exebridge, hourly gauge-readings for the first day may be recorded, and at Exeter hourly readings for the second day, and these cannot be compared. Table IX. exhibits all flood-records which can be compared.

TABLE IX.—EXE RIVER FLOODS.

Date.	High water.			Brampford Speke.		Time of Passage. Hours.	
	Exebridge.	Brampford Speke.	Exeter Quay.	Gauge.	Discharge.	Exebridge to Brampford Speke.	Brampford Speke to Exeter.
				ft. ins.	Cusecs.		
5.12.07	8 a.m.	10 a.m.	2 p.m.	7 0	2960	2	4
1.9.08	3 p.m.	7.30 p.m.	—	4 4	1566	4·5	—
31.12.08	6 p.m.	10 p.m.	—	4 4	1566	4	—
9.3.09	—	4 a.m.	9 a.m.	6 1	2414	—	5
16.10.09	3 a.m.	9 a.m.	—	7 8	3409	6	—
3.12.09	2 a.m.	9 a.m.	noon	8 0	3635	7	3
24.1.10	—	7.45 a.m.	11 a.m.	7 10	3522	—	3·25
13.10.10	—	11 a.m.	3 p.m.	7 9	3465	—	4
1.11.10	noon	6.30 p.m.	—	8 2	3765	6·5	—
13.12.10	10 a.m.	3.30 p.m.	5 p.m.	6 10	2860	5·5	1·5
16.12.10	—	1.30 p.m.	4 p.m.	7 11	3578	—	2·5
25.2.11	1 p.m.	5.15 p.m.	—	5 2	1978	4·25	—
28.2.11	2 p.m.	6.15 p.m.	—	6 4	2563	4·25	—
					Average	4·9	3·3

Exebridge to Brampford Speke = 22·5 miles.
Brampford Speke to Exeter = 6 miles.

There is one interesting point about these records: there is at least an indication that the crest-wave of high floods takes longer to pass down the valley than the crest-wave of moderate floods. In the upper portion of the river the channel is deep, and floods do not spill over the banks, but in the lower reaches the river has a broad shallow section, and floods spread out laterally to a considerable distance.

A moderate flood is contained in the actual channel of the river and travels quickly, while a high flood spreads out laterally in the lower reaches and the velocity of the flood-crest is reduced. This is merely a guess at the cause of the comparatively low velocity of high floods, but so far as these records show, moderate floods do travel more quickly than high floods, which is the opposite of what one would naturally expect to find.

From January 1, 1907 to March 31, 1912 the gauges at Brampford Speke and Exeter were read daily. These daily gauge-readings were converted into volumes by means of the discharge curves, and from these daily volumes the various discharge and percentage diagrams have been compiled and plotted.

The discharge diagrams for the Exeter quay gauge do not take into account the volume of water taken out of the river for the water supply of Exeter City. This volume is practically constant and amounts to 730 million gallons per annum, equivalent to a continuous discharge of 3·7 cusecs. Taking this comparatively small volume into account, the effect is to increase slightly the percentage of the rainfall run off by the river. On the average of five years the percentage run off as shown on the diagrams is too low by 0·26 per cent.

THE CULM AND THE CREEDY.

In addition to the two discharge sites on the Exe at Brampford Speke and Exeter, it was proposed originally to establish discharge sites on the Culm and Creedy, and to collect separate data for the catchment areas of these tributaries. To be of practical value the sites should be somewhere near the junctions of the tributaries with the Exe.

On the Culm no satisfactory site was discovered; the river-banks are so low that in floods a great volume of water spreads over the low-lying valley, and to find a well-defined channel it would have been necessary to go high up the river, so that a portion only of the catchment area would be included in the discharge measurements.

On the Creedy, although a fairly satisfactory site was available at Pynes Bridge, it was found that in floods the water from the Exe backed up into the Creedy so that flood gauge-readings at this point would give no reliable indication of the discharge.

In view of these practical difficulties it was determined to concentrate observations on the Exe itself and to leave work on the tributaries to the future. Daily gauge readings were recorded on the Culm and Creedy, but there are no data for converting these into volumes of water. The gauge on the Culm was erected on a bridge near Silverton Station, and was read by Mr. Charles Gray, Engineer to the Silverton Paper Mills; that on the Creedy was at Pynes Bridge, and was read by an employee of the Exeter City Council. These gauges would be useful if the investigation is continued later on. It would probably be found necessary to construct an artificial discharge site on the Culm by embanking a short portion of the river to prevent spill; and on the Creedy it would be necessary to establish a discharge site beyond the reach of the Exe backwater, or to determine a connection between flood gauges and discharges on the Creedy with corresponding flood gauges on the Exe.

THE MEDWAY.

On the Medway, which is canalized, the conditions are different from those on the Exe, and a gauge-reading gives no indication of the volume of water passing down the river, as navigation depth is maintained by manipulation of the lock-sluices, whatever may be the discharge. It was therefore decided to calculate the

discharge from the slope of the water-surface, the slope being got from two gauges at a known distance apart, with their zeros fixed at known levels for comparison. As the conditions governing the surface slope are continually altering, it was necessary that the gauges should be self-recording.

Given the slope of the water-surface, the mean velocity is got from the expression $v = C\sqrt{RI}$, where R is the hydraulic radius, and I is the fall of the water-surface in unit length. C is a coefficient which varies with the rugosity, surface slope, and hydraulic radius. The equation for C which it was proposed to use is the well-known formula of Kutter, which is based on the experimental investigations of Kutter and Ganguillet—

$$C = \frac{\left(41{\cdot}6 + \frac{1{\cdot}811}{N} + \frac{0{\cdot}00281}{I}\right)\sqrt{R}}{\sqrt{R} + N\left(41{\cdot}6 + \frac{0{\cdot}00281}{I}\right)}$$

where N = Kutter's coefficient of rugosity.

Two self-recording gauges were erected 10,000 feet apart, one, by permission of Mr. W. E. Martin, in a well close to the river-bank in his garden at Maidstone, and the other by permission of Mr. Randall Mercer in his boat-house above Allington lock.

The general arrangement of the gauges was as follows:—a vertical drum actuated by an eight-day clock was connected to a float in the well and the well itself communicated with the river by a small pipe. The fluctuations of level in the river were recorded by a pencil connected with the float, which marked a continuous line on a paper wrapped round the revolving drum. To keep the pencil record within reasonable limits the movement of the float was communicated to the pencil by reducing gear so that the float movements were reduced to one-sixth, a variation of a foot in water-level appearing as a variation of two inches on the pencil record. Each record covered a period of a week.

To arrive at the slope of the water-surface from the records of the self-recording gauges it was necessary to determine the relative levels of the gauge-zeros. This was done by levelling several times between the gauges and finally the relative levels were arrived at with a possible error of $\pm$ 0·01 foot, which was accepted as satisfactory. The measurements required for the mean cross-section of the river between the gauges were taken in the usual way by soundings from a boat.

To use Kutter's discharge formula it was also necessary to determine the value of N, the coefficient of rugosity. This was done by measuring a series of discharges by the surface float method. The surface slope for each discharge was got from the gauge records, and from actual measurement a final value N = 0·030 was arrived at.

These preliminary measurements were carried out by myself, assisted by General Strahan and Mr. Yorke.

During the period occupied by these preliminary investigations the self-recording gauges were at work, and it was evident that the records were not entirely satisfactory. A serious difficulty was that the clocks of the two gauges did not synchronize, and this difficulty continued during the period covered by the investigations.

The pencil record of the water-level was also found unsatisfactory. Instead of being a clean-cut line there were marked oscillations.

The diagram, Fig. 6, is a reduced reproduction of an actual record, and where the oscillations appear, it is difficult to determine the actual gauge-reading. These oscillations were found to be caused by wind waves in the river which were communicated to the gauge well. This difficulty was overcome by reducing the pipe connection between the river and the gauge well, but after this had been done it

WATER-LEVEL RECORD: OLD COLLEGE GAUGE. SCALE: $\frac{1}{4}$ FULL SIZE.

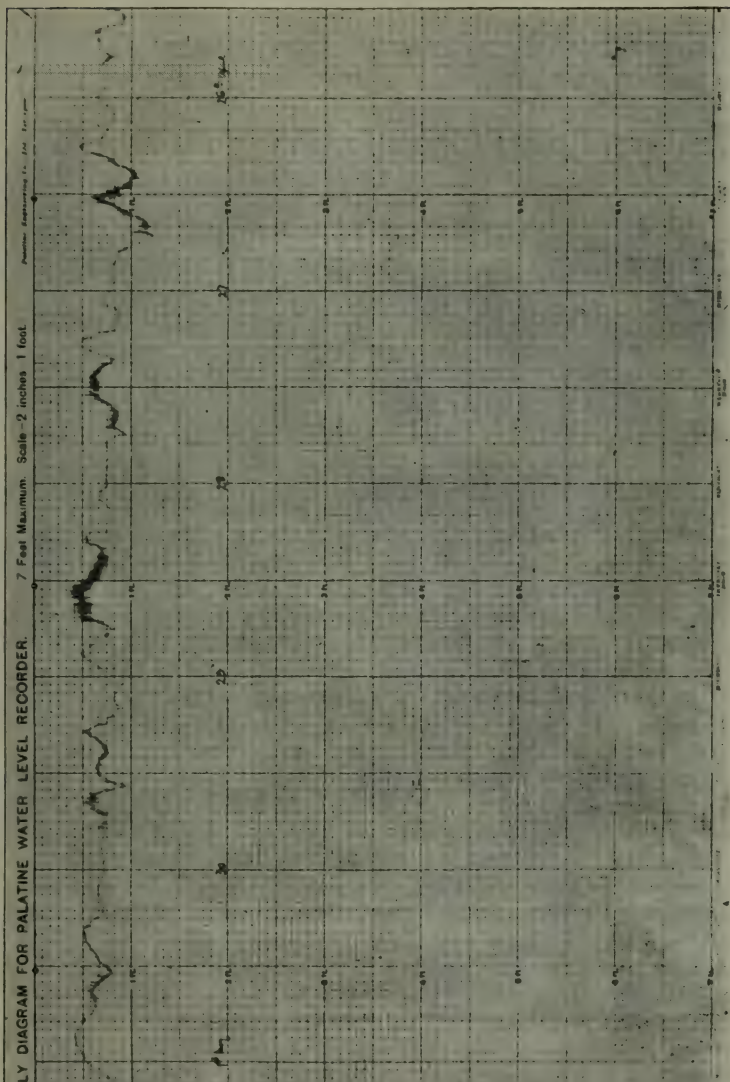


FIG. 6.

was still found that passing boats and barges produced waves and fluctuations which seriously affected the record of water-levels.

There were numerous interruptions also due to minor mishaps to the mechanism of one or other of the gauges, and one record without the other was of no value.

The surface slope of the canalized portion of the Medway is exceedingly small; in some 2500 pairs of gauge-readings, 75 per cent. give a slope of 1 inch or less in 10,000 feet. Under such conditions the determination of the discharge required a precise, continuous, and synchronous record of surface slopes. Unfortunately the method adopted failed, more or less, in all these requirements. No doubt more elaborate arrangements would have produced better results; for example, an electric control would have secured the synchronous working of the clocks. The methods adopted were governed by financial considerations and funds were limited. The experience gained on the Medway proves that for accurate results something more elaborate (and more expensive) than the method adopted is really required.

The measurements of surface slopes were continued for a period of three years, and the net result was a fairly continuous record of discharge for twelve months, from September, 1908, to August, 1909, and for a separate period of five months, April to August, 1910.

For working out the daily discharges a table of final results was first prepared, based on the previously determined value (0·030) of the coefficient of rugosity. This contained discharges for all gauges up to $4\frac{1}{4}$ feet, advancing by inches, and for all surface slopes up to 4 feet, advancing by eighths of an inch. A specimen page of this table is herewith printed (Table X.).

To arrive at the discharge for any one day, the mean gauge and the surface slope were taken from the gauge records, allowance being made for the difference of level of the gauge-zeros. The discharge corresponding to these data was then got from the table of final results. The data were taken at intervals of three hours, so that each daily discharge is the mean of eight separate computations.

When working out the discharges, a curious phenomenon presented itself:—

It not unfrequently happens that after correction for difference of level of gauge-zeros, the downstream gauge reads higher than the upstream gauge, *i.e.* the river apparently flows upstream. An obvious explanation of this phenomenon at once suggests itself, viz. that there is a mistake in the levels of the gauge-zeros. The gauge zeros were levelled in 1909 three times over with results which were practically identical, leaving a possible error of one-eighth inch in 2 miles. To check the levels the work was done a fourth time, and the result exactly confirmed the former results. There is therefore no error in the levelling beyond the possible error of one-eighth inch, which cannot be eliminated.

This reverse surface slope appears under two different sets of conditions. When the river is low, very nearly a still water channel, the reverse slope is always accompanied by oscillations on the gauge record due to wind; and in these conditions the reverse slope occasionally lasts for many hours until the wind drops; on one occasion it lasted for twenty-four hours, but that was quite exceptional, and during the whole of the period the lower gauge record shows oscillations of about 3 inches, while the upper gauge was in shelter, and its record is a clean-cut line. The reverse slope appears very occasionally during moderate floods, and is not necessarily accompanied by oscillations on the records; it may and does occur during a dead calm. In such cases it never lasts any length of time, and is probably caused by the sudden closing of some of the sluices at Allington lock, which is some 3 furlongs below the downstream gauge.

The difficulty connected with these reverse slopes is in determining the discharge of the river when they occur. Notwithstanding the apparent upstream flow of the

TABLE X.—RIVER MEDWAY: DISCHARGE TABLE.

Slope.	Mean Gauge.																											
	in. 9	in. 10	in. 11	in. 12	in. 13	in. 14	in. 15	in. 16	in. 17	in. 18	in. 19	in. 20	in. 21	in. 22	in. 23	in. 24	in. 25	in 26	in. 27	in. 28	in. 29	in. 30	in. 31	in. 32	in. 33	in. 34	in. 35	in. 36
in. $\frac{1}{8}$	324	328	333	**338**	342	347	352	356	361	366	371	376	381	386	391	**397**	402	407	413	418	423	429	434	439	445	450	455	**461**
$\frac{1}{4}$	451	457	464	**471**	477	484	491	497	503	510	517	524	532	539	546	**553**	560	567	574	581	588	595	602	609	617	624	632	**640**
$\frac{3}{8}$	543	551	559	**567**	574	582	590	597	605	613	621	630	639	647	656	**665**	673	681	690	698	707	716	724	733	742	751	760	**769**
$\frac{1}{2}$	624	633	642	**651**	659	667	676	685	694	704	719	735	751	760	769	**779**	789	799	810	813	817	821	831	841	851	861	871	**881**
$\frac{5}{8}$	688	698	708	**719**	728	738	748	757	767	777	787	798	809	820	831	**842**	852	863	874	881	888	906	917	928	939	950	961	**972**
$\frac{3}{4}$	750	760	770	**781**	792	803	815	825	835	845	856	867	879	890	902	**914**	925	936	948	958	970	982	993	1005	1017	1028	1040	**1052**
$\frac{7}{8}$	803	814	826	**838**	849	860	871	882	893	904	916	928	941	953	966	**979**	991	1003	1015	1027	1039	1052	1064	1077	1090	1102	1115	**1128**
1	**847**	**859**	**871**	**883**	**894**	**906**	**918**	**930**	**942**	**954**	**967**	**980**	**993**	**1006**	**1019**	**1032**	**1044**	**1057**	**1070**	**1083**	**1096**	**1109**	**1122**	**1135**	**1149**	**1162**	**1175**	**1189**
$1\frac{1}{8}$	891	903	915	**927**	938	950	962	975	988	1002	1015	1029	1043	1056	1070	**1084**	1097	1110	1123	1136	1149	1163	1177	1191	1205	1219	1233	**1247**
$1\frac{1}{4}$	935	947	959	**972**	983	994	1006	1020	1035	1050	1064	1078	1093	1107	1121	**1136**	1149	1163	1177	1190	1204	1218	1232	1246	1261	1275	1290	**1305**
$1\frac{3}{8}$	975	988	1001	**1014**	1026	1039	1052	1066	1080	1095	1109	1124	1139	1154	1169	**1184**	1198	1212	1227	1241	1255	1270	1285	1300	1315	1330	1345	**1360**
$1\frac{1}{2}$	1015	1029	1043	**1057**	1069	1083	1098	1112	1126	1140	1155	1170	1186	1201	1216	**1232**	1247	1262	1277	1292	1307	1322	1337	1353	1369	1384	1400	**1416**
$1\frac{5}{8}$	1045	1059	1073	**1088**	1102	1116	1130	1144	1158	1173	1188	1204	1220	1235	1250	**1266**	1281	1296	1312	1327	1343	1359	1375	1391	1408	1426	1444	**1462**
$1\frac{3}{4}$	1075	1090	1105	**1120**	1134	1148	1163	1177	1192	1207	1222	1238	1254	1269	1285	**1301**	1316	1332	1348	1364	1380	1396	1413	1430	1447	1464	1481	**1498**
$1\frac{7}{8}$	1107	1122	1137	**1153**	1167	1182	1197	1212	1227	1242	1258	1274	1291	1307	1324	**1341**	1357	1373	1389	1405	1421	1437	1454	1471	1489	1506	1523	**1541**
2	**1139**	**1154**	**1170**	**1186**	**1210**	**1216**	**1232**	**1248**	**1263**	**1278**	**1295**	**1312**	**1329**	**1346**	**1363**	**1381**	**1397**	**1413**	**1430**	**1446**	**1462**	**1479**	**1496**	**1513**	**1531**	**1548**	**1566**	**1584**

river, there must be some water passing downstream, and no practical method of arriving at the discharge could be devised. In computing the discharge records, the periods when the lower gauge read higher than the upstream gauge were therefore omitted.

In conclusion, a possible method of gauging a canalized river like the Medway may be suggested, viz. by calculating the discharge passing through the lock sluices. Given the width of the sluices, the height to which they are opened, and the head, the volume passing through the openings can be calculated. This would mean an establishment constantly on the spot to keep a continuous record of alterations in the area of the sluice openings and of the upstream water-level. Given the necessary establishment, this method, though laborious and involving much computation, would be more satisfactory than the surface slope method. The upstream water-level, *i.e.* the head on the sluices, could be determined by a self-recording gauge which, being a single gauge, would not be required to synchronize with any other.

CURVES SHOWING RAINFALL AND DISCHARGE.

By N. F. MACKENZIE, M.Inst.C.E.

After the various discharge data had been compiled, the figures of daily rainfall over the several catchment areas were supplied by Dr. Mill, and the method he adopted for their compilation is described in his Report. The rainfall was expressed in inches per 24 hours, and was converted into an equivalent continuous discharge in cusecs by the formula :—

$$C = 26{\cdot}89AI$$

where I = rainfall in inches in 24 hours,

A = area of the catchment in square miles,

and C = continuous discharge in cusecs equivalent to the rainfall.

From the daily records of rainfall and discharge, tables of monthly, six-monthly, and yearly means were prepared, and these tables were used for plotting the corresponding curve diagrams. For the Medway a table of monthly means only was prepared, as the period for which daily discharges had been arrived at was too short to be of use for six-monthly or for yearly means.

The mean rainfall for 1907–11, taken from Dr. Mill's report on the Exe catchment, has been used as a check on the conversion of the daily rainfall into equivalent continuous discharges. The results are as follows :—

	Brampford Speke.	Exeter.
Mean rainfall 1907–11 from report	832 cusecs.	1388 cusecs.
Mean of daily rainfall from tables	831 „	1378 „

These are practically identical.

The following curve diagrams were plotted :—

For the Exe at Exeter and at Brampford Speke.

1. Daily rainfall and discharge 1907–1911, one year on each diagram. (Of these the diagrams for 1911 only are reproduced)* (Plates 4 and 5).

* The year 1911 has been selected as an example of daily rainfall and discharge curves, as the diagrams show clearly how little a considerable fall of rain on a dry catchment area affects the discharge of the river; the rainfall is nearly all absorbed and evaporated.

2. Mean monthly rainfall and discharge 1907–1911 (Plate 6, Figs. 1 and 4).
3. Mean six-monthly rainfall and discharge 1907–1911 (Plate 6, Figs. 2 and 5).
4. Mean yearly rainfall and discharge 1907–1911 (Plate 6, Figs. 3 and 6).
5. Diagram showing percentage of rainfall lost based on monthly means (Plate 7, Figs. 1 and 4).
6. Diagram showing percentage of rainfall lost based on six-monthly means (Plate 7, Figs. 2 and 5).
7. Diagram showing percentage of rainfall lost based on yearly means (Plate 7, Figs. 3 and 6).
8. Curve showing the relation between loss and rainfall (Fig. 7).

For the Medway.

1. Daily rainfall and discharge	From September, 1908 to August, 1909, and from April to August, 1910.	Plate 8.
2. Mean monthly rainfall and discharge ...		
3. Percentage diagram based on monthly means		

As noted in the report on the Severn, the irregularities in the curves of rainfall and discharge, which are very marked in the daily diagrams, tend to disappear as the period for which mean values are taken is increased; in the diagrams of yearly means the curves are approximately parallel. It will be seen that in the curves of monthly means the discharge is occasionally greater than the rainfall. The explanation is that during very dry periods, such as the summer of 1911, though there is little or no surface drainage, the river is fed by springs and never runs quite dry.

The concavity of the discharge curve of a falling river is found on the Exe as on the Severn, though the convexity of the upper portion of the curve of a rising river is not so marked. This is due to the method followed in drawing the curve; the points plotted for daily discharges were joined by straight lines, and no attempt was made to join these points by a smooth curve. The Exe has a catchment area of 461 square miles, and the discharge peaks appear to lag behind those of the rainfall by about one day, though when rainfall follows a spell of dry weather the lag is somewhat greater.

The yearly rainfall and loss have been plotted (Fig. 7) for the two Exe areas in the same way as for the Severn, and with much the same result, it is possible to draw a smooth curve through or near the plotted points. The year 1907 for the Brampford Speke area is, however, a marked exception; the quantity of rainfall not accounted for by the discharge is 44 per cent., whereas to bring the plotted point on to the general curve the loss should be 51 per cent. of the rainfall. The explanation seems to lie in the weather conditions which prevailed during the five months April–August, 1907, these months were abnormally wet and cold. At Collumpton, on the Culm, rain was recorded on 92 of the 153 days, and at Allington, close to Exmoor, there was rainfall on 93 days. Persistent weather conditions of this sort would cause a considerable falling off both in evaporation and in absorption, and a greater percentage of the rainfall would appear as river discharge. At Brampford Speke the mean discharge for April–August, 1907, was 43 per cent. of the rainfall, while the mean for the same period during the next 4 years was 34 per cent. only. It is not clear why the upper part only of the basin was affected, but too much stress must not be laid on these curves as they cover the results of 5 years only. They, however, support the general conclusion that a greater percentage is lost when the rainfall is light than when it is heavy.

TABLE XI.—RIVER EXE.

Rainfall and Discharge.

Monthly and Yearly Means.

	1907.			1908.			1909.			1910.			1911.			1912.			
	Rainfall.	Discharge.	Discharge as per cent. of Rainfall.	Rainfall.	Discharge.	Discharge as per cent. of Rainfall.	Rainfall.	Discharge.	Discharge as per cent. of Rainfall.	Rainfall.	Discharge.	Discharge as per cent. of Rainfall.	Rainfall.	Discharge.	Discharge as per cent. of Rainfall.	Rainfall.	Discharge.	Discharge as per cent. of Rainfall.	
									Brampford Speke.										
Jan.	487	392	80·5	644	548	85·1	609	721	101·9	1478	1084	73·4	437	476	108·9	1259	1079	85·7	Percentage of rainfall discharged (5-year mean) = 52·6.
Feb.	597	512	85·7	736	457	62·1	181	168	92·8	1653	1186	71·7	884	397	44·9	847	608	70·6	
March	351	326	92·6	860	591	68·7	1197	598	50·0	215	393	182·8	612	717	117·1	1766	1264	71·5	
April	1145	509	44·4	693	312	45·0	800	400	50·0	750	242	32·1	709	197	27·7	—	—	—	
May	661	423	64·0	460	350	76·1	464	221	47·6	782	339	43·3	369	342	92·7	—	—	—	
June	836	260	31·1	186	92	49·4	610	127	20·8	1008	167	16·5	761	72	9·4	—	—	—	
July	511	276	54·0	661	104	15·7	648	86	13·2	887	223	25·1	76	56	73·7	—	—	—	
August	794	259	32·6	1091	81	7·4	495	73	14·7	1258	415	22·9	443	36	8·1	—	—	—	
Sept.	193	104	53·8	871	364	41·7	730	93	12·7	80	256	320·0	572	34	5·9	—	—	—	
Oct.	1581	429	22·1	612	274	44·7	1917	1073	55·9	1898	663	34·9	979	99	10·1	—	—	—	
Nov.	737	531	72·0	607	335	55·1	762	327	42·9	1679	1070	63·7	1293	743	57·4	—	—	—	
Dec.	1362	1159	85·1	1018	605	59·4	1440	854	59·3	1612	1470	91·2	2400	1523	63·4	—	—	—	
Yearly Mean	771	432	56·0	698	343	49·3	810	395	48·8	1085	626	57·7	793	391	49·3	—	—	—	—
									Exeter.										
Jan.	770	490	63·6	1046	967	92·4	937	1191	127·1	2408	1806	75·0	641	869	135·5	2148	1788	83·2	Percentage of rainfall discharged (5-year mean) = 56·3.
Feb.	918	458	49·8	1163	812	69·0	285	444	155·8	2680	1875	70·0	1242	644	51·8	1511	1102	72·9	
March	509	576	113·1	1530	1008	65·9	2232	1271	56·9	324	790	243·8	1054	1125	106·7	2973	2097	70·5	
April	2118	937	48·2	1193	674	56·5	1300	781	60·0	1295	525	40·5	1133	478	42·1	—	—	—	
May	1206	787	65·2	810	677	83·6	705	475	67·3	1385	650	46·9	617	615	99·6	—	—	—	
June	1296	491	37·8	306	315	102·9	1149	345	30·0	1128	392	34·7	1223	324	26·5	—	—	—	
July	793	473	59·6	854	295	34·5	1122	323	28·8	1422	414	29·1	140	282	201·4	—	—	—	
August	1134	436	38·4	1700	335	19·7	873	332	38·0	2164	757	34·9	860	297	34·5	—	—	—	
Sept.	324	320	98·7	1387	608	43·8	1134	299	26·3	137	478	348·9	919	257	28·0	—	—	—	
Oct.	2945	818	27·4	1190	496	41·7	2997	1431	47·7	3161	1137	36·0	1780	365	20·5	—	—	—	
Nov.	1338	937	70·0	828	485	58·5	780	522	66·9	2811	1754	62·3	2158	1157	53·6	—	—	—	
Dec.	2360	1943	82·3	1737	920	52·9	2493	1855	74·4	3033	2633	86·8	4295	2770	64·5	—	—	—	
Yearly Mean	1289	722	56·0	1090	633	58·1	1350	772	57·1	1827	1101	60·2	1332	765	57·4	—	—	—	—

TABLE XII.—RIVER EXE.

Rainfall and Discharge.

Six-monthly Means.

	Brampford Speke.			Exeter.		
	Rainfall.	Discharge.	Discharge as per cent. of rainfall.	Rainfall.	Discharge.	Discharge as per cent. of rainfall.
Summer, 1907 ...	688	305	44·2	1146	607	53·0
Winter, 1907–08	987	619	62·7	1730	1080	62·4
Summer, 1908 ...	660	217	32·9	1058	484	45·7
Winter, 1908–09	704	450	63·9	1202	801	66·7
Summer, 1909 ...	625	167	26·7	1047	426	40·7
Winter, 1909–10	1244	820	65·9	1945	1380	70·9
Summer, 1910 ...	794	274	34·3	1255	536	42·7
Winter, 1910–11	1187	797	67·1	1990	1377	69·2
Summer, 1911 ...	488	123	25·2	816	376	46·1
Winter, 1911–12	1423	886	62·2	2477	1546	62·4

Winter months taken as October to March inclusive.
Summer months taken as April to September inclusive.

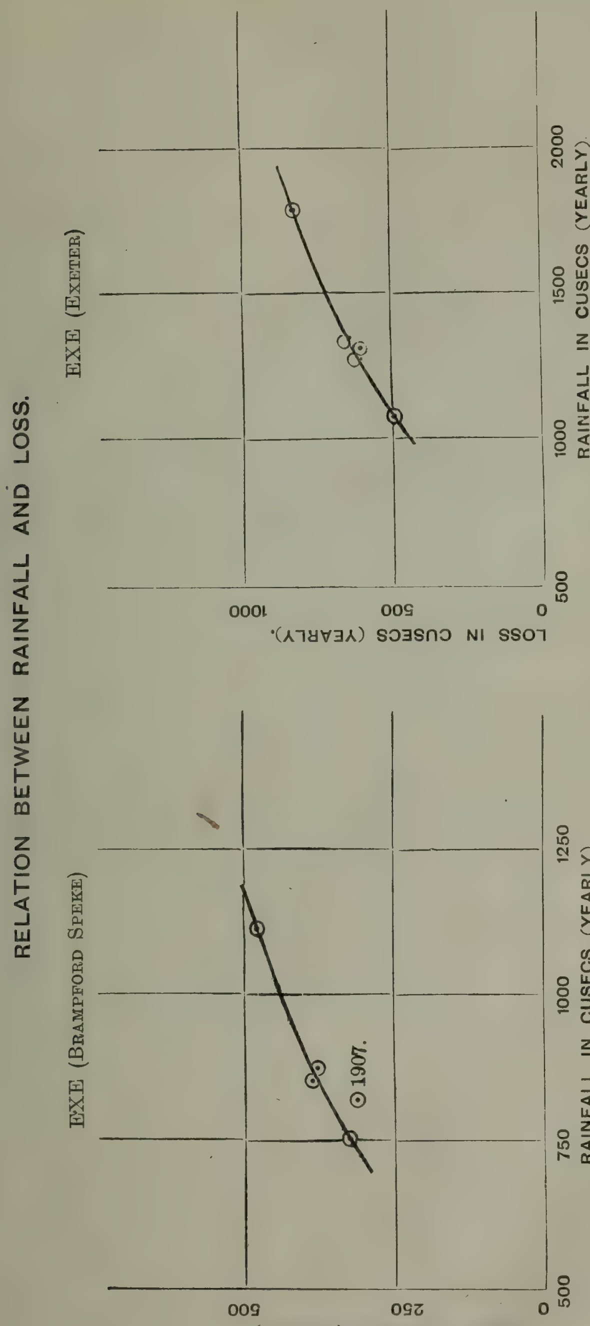

RELATION BETWEEN RAINFALL AND LOSS.
EXE (Exeter)
LOSS IN CUSECS (YEARLY).
0
500
1000
RAINFALL IN CUSECS (YEARLY)
500
1000
1500
2000
EXE (Brampford Speke)
LOSS IN CUSECS (YEARLY).
0
250
500
RAINFALL IN CUSECS (YEARLY)
500
750
1000
1250
1907.

Fig. 7.

TABLE XIII.—RIVER MEDWAY.

RAINFALL AND DISCHARGE.

Monthly Means.

		Rainfall.	Discharge.	Discharge as per cent. of rainfall.
1908.	September	747	547	73·2
	October	898	466	51·9
	November	601	909	151·2
	December	1550	743	47·9
1909.	January	512	836	163·3
	February	342	565	165·2
	March	2012	1866	92·7
	April	873	906	103·8
	May	683	642	94·0
	June	1496	360	24·1
	July	1622	777	47·9
	August	1209	678	56·1
1910.	April	1026	602	58·6
	May	1344	632	46·0
	June	1114	396	35·5
	July	1325	656	49·5
	August	1202	595	41·2

REPORT ON THE AVERAGE ANNUAL RAINFALL OF THE EXE VALLEY.

By HUGH ROBERT MILL, D.Sc., LL.D.

The problem of ascertaining the average quantity of precipitation which falls upon a given area in a long series of years, resolves itself into the construction of a rainfall map from the records of irregularly distributed stations, continued for a variable number of years and of different degrees of accuracy. The accuracy of the observations depends on the use of proper instruments suitably exposed and regularly examined. In most cases it is easy to detect gross errors, such as an annual total which is more than 10 inches too high or too low, and returns which are clearly erroneous are excluded from the annual volumes of 'British Rainfall,' the source from which practically all the data used have been obtained. Errors of smaller amount, though often suspected, are not always demonstrated before the publication of the annual volume, and the only practicable test is the general congruence of the whole series of figures for a particular year when placed on a map.

It need not be insisted upon that one of the main objects in using the average of a long series of years is that accidental errors may either be eliminated or so reduced as not to affect the final result seriously. In favourable circumstances, it is possible to compute the long-period average of short records, by comparing them

with the corresponding portions of neighbouring records running through the whole period chosen for the average, and this is the method usually adopted; but it can only be done when at least one complete record exists for each of the natural regions of the area, as it is rare to find uniform differences from the average prevailing over any large extent of country in any one year.

The number of long records in the Exe Valley or on its borders is not sufficient to justify the use of this method, which was successfully employed in constructing the maps of average rainfall prepared for the Water Supply Memoirs of the Geological Survey for districts where long records are more numerous. It was therefore found necessary to construct a series of short-period maps which could be subsequently combined to yield a map of average rainfall for a much longer period. It was convenient to use ten years for the short-period means, and possible to utilize four decades of observations. The operations included (1) Testing the available data; (2) compiling maps for four successive periods of ten years each; (3) combining the four into one average map for forty years; (4) computing the general average rainfall of the various tributary streams and of the whole valley; (5) discussing the distribution of annual rainfall in space and time.

The number of stations for the observation of rainfall before 1868 was so small, that it was found impracticable to carry the discussion further back than that year; but a map was constructed for each of the decades, 1868–1877, 1878–1887, 1888–1897, 1898–1907, from data which are summarized in the accompanying tables. As this method of procedure has not been used before as far as I know, it may be desirable to describe it in some detail. In mapping the 2500 square miles of country including and surrounding the valley of the Exe, 173 separate rainfall-records were dealt with, the duration ranging from 1 to 40 years as follows:—

Years' duration ...	1–4	5–9	10–14	15–19	20–24	25–29	30–34	35–40	Total.
No. of records ...	49	37	38	14	14	6	6	9	173

The total number of yearly values was 2101, and on the very moderate computation of 200 rain-days in the year, this represents about 420,000 separate readings of the rain-gauge. Very many of the records would have been lost—and a large number would never have started—but for the constant watchfulness of the successive editors of 'British Rainfall,' and the continuous efforts made to secure accurate observations and careful records. Practically, the whole of the observations were carried out by voluntary amateur observers.

The first step in the case of each ten-yearly period was to write out the total annual rainfall for all the stations comprised in the Exe valley and the surrounding country, the whole area dealt with being a stretch of 52 miles by 48, and the Ordnance map on the scale of 4 miles to 1 inch was chosen for plotting the results. In each period, the records were complete for ten years at a number of stations, and the ten-year means of these expressed to the nearest half-inch were placed upon the map. At a number of stations means of less than ten years were available, and as these means might refer to a period either wetter or drier than the mean of ten years, it would obviously be misleading to place them on the map without correction. The most convenient mode of correction is to apply to the mean of, say, five years the ratio which the same five years of a complete decade bears to the whole, using for this purpose the mean ratio for the period at several contiguous stations with complete records. For example, if at a particular station five years' records gave a mean of 40 inches, and at three neighbouring stations with complete records, the ratios of the mean rainfall of that period of five years to the whole ten-year period were respectively 85, 87, and 83 per cent., the mean ratio would be 85 per cent.,

and the 40 inches would have to be increased in the ratio of 85 to 100, *i.e.* to 47 inches, in order to represent the computed average for ten years. The figures in Table XIV. thus yielded actual or computed averages which were scattered over the four ten-year maps somewhat irregularly, and as the individual stations represented were not always the same in successive periods, a further calculation was made by which the rainfall for each station occurring in any decade could be represented on the map of another decade by a computed value. To arrive at this result, a series of percentages was worked for all the stations represented on two or more maps falling into six groups, thus—

(1)	Rainfall on Map	I	expressed as	percentage of	rainfall on Map	II.	
(2)	,,	I	,,	,,	,,	III.	
(3)	,,	I	,,	,,	,,	IV.	See pp. 40, 41.
(4)	,,	II	,,	,,	,,	III.	
(5)	,,	II	,,	,,	,,	IV.	
(6)	,,	III	,,	,,	,,	IV.	

All the percentages of group (1) were plotted on a map, and it was found that, as a rule, the values varied regularly from one part of the area to the other. Values that were very discordant with those around them were disregarded, and the percentage which corresponded to a point on Map I where there was no figure on that map, but where a figure occurred on Map II, could be read off by inspection. The value on Map II (decade 1878–1887), reduced or increased in the ratio of the particular percentage to 100, was then placed as a computed mean on Map I (decade 1868–1877). It might be that these computed values were obtained for the same point from several different decades, and when this was so, a mean was taken. This process, worked out for each of the groups, supplied a number of supplementary points on each map, which, though less trustworthy than the points for which direct values were available, might yet supply useful indications of the direction of the isohyetal lines. At best the distribution was irregular, and observations were most deficient in the valley of the Creedy and the whole district between Dartmoor and Exmoor west of the main river Exe, where consequently the run of the isohyets is less decided than in other parts of the region.

It was obvious on each of the maps that the distribution of average annual rainfall was governed by the configuration of the country taken in conjunction with the direction of the prevailing wind. The estuary of the Exe was always the driest portion; Dartmoor and Exmoor were two dominating centres of high rainfall, and a third centre of moderately high rainfall occurred on the hills of eastern Devon. The four maps (which are reproduced on a small scale) were so closely similar in the run of the isohyets that there could be no doubt as to the general character of the distribution of rainfall, and by extending the area far beyond the Exe Valley on every side, it was possible to draw the lines across the valley with far more confidence than if attention had been strictly confined to the actual area the hydrographical conditions of which were under discussion.

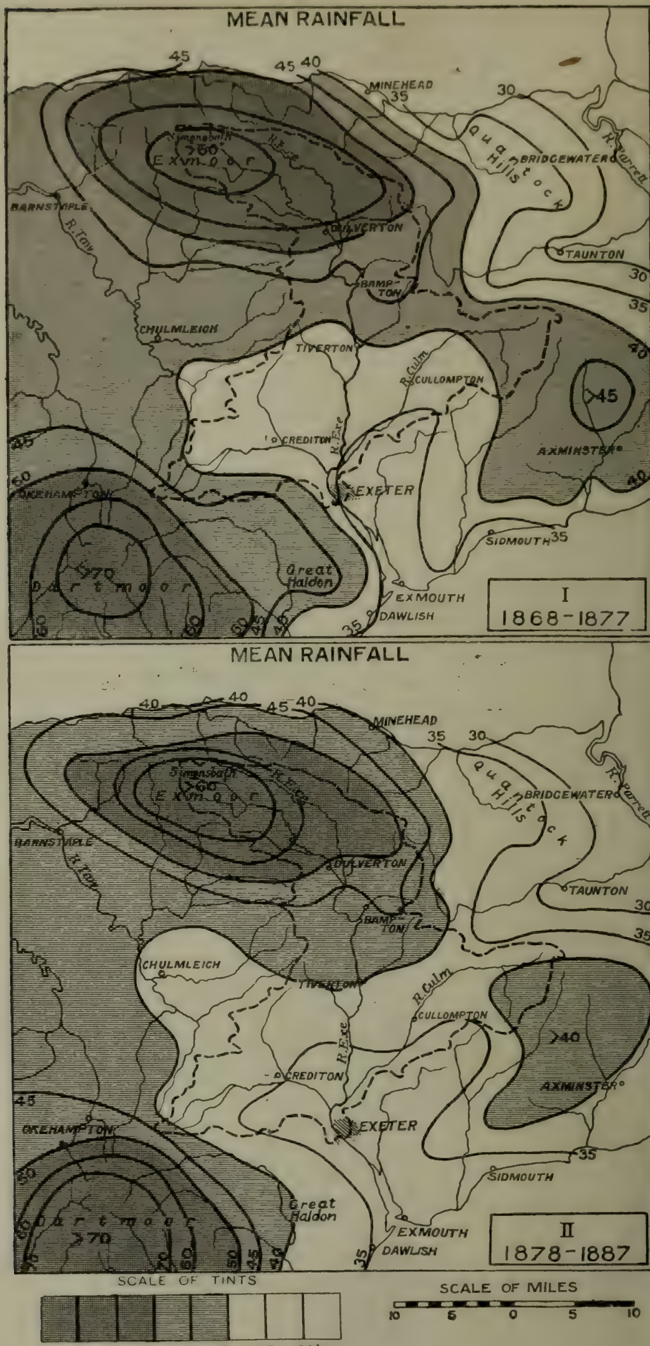
The combination of the four maps of ten-year means into one map of forty years' average presented several points of difficulty. Two entirely different methods were employed with a satisfactory degree of accordance. The first method consisted of tracing off an isohyet of a given value separately from two of the maps and drawing the mean curve between them, repeating this for the other two maps on the same piece of tracing-paper, and then drawing the mean of the two mean isohyets, which, of course, corresponded to the forty years' average. This method was found to act perfectly for all the isohyets at intervals of 5 inches above

40 inches, as these occur on all the maps, but it was somewhat at fault for those of 30 and 35 inches, which occur only on some maps, and quite ineffective for the line of 40 inches, which on one occasion formed a single curve surrounding the dry central area, on two occasions a curve surrounding the dry area only on the west and north, and on the fourth a set of separate curves surrounding the various wet areas. The method could only be fully satisfactory if the periods compared were long enough to reduce the differences to so small an amount that all the isohyets of the same name were similar in form on the several maps. The method might indeed be employed to deduce an average map from a very large number of separate annual maps by a process akin to making composite photographs of each isohyet line in all the maps, the average position of the isohyet standing out as the result of all the impressions; but the number of individual maps would require to be very great in order to eliminate the disturbing effect of extreme cases.

The other method used consisted in ruling up each map into a network of numbered squares. The number actually used was 19 equidistant vertical lines crossed by 17 equidistant horizontal lines; and of the 323 intersections thus made, 294 fell on the land. The closest approximation to the value of the rainfall at each intersection which could be arrived at by inspection of the isohyetal lines and actual figures was written down, and the means of the values at each intersection on the four maps were used to construct an average map from 294 equidistant points, upon which a fresh set of isohyets was drawn. The map thus produced corresponded so closely with the map made by compounding the isohyets (except in the case of the line of 40 inches), that both systems must be viewed as yielding identical results for the wetter part of the area; but in the drier parts the mean of the intersections of course gave definite isohyets in places where the dissimilar forms of the lines made it impossible to arrive at them by the first method, and I have no hesitation in accepting the map constructed from the 294 points as the closest approximation to the actual distribution of rainfall which the data can yield, and the map is accordingly reproduced here, facing p. 48, and used in the following discussion.

Adopting the map of average rainfall 1868–1907, prepared by the second method, as representing the normal distribution of rain over the Exe valley and its surroundings, we are in a position to discuss the relation of precipitation to the configuration. As was to be expected, the heaviest rainfall occurs on Dartmoor, where a wide area round Princetown has certainly more than 70 inches per annum. So far as can be judged, the wettest part of Dartmoor lies to the south of the highest point; but the absence of records on the northern slope of the moor makes the exact position of the higher isohyets somewhat uncertain. The rainfall diminishes rapidly in all directions, and the extreme western point of the Creedy valley just touches the 45-inch line. The diminution of rainfall is least rapid towards the east, but this is seen chiefly in the wide sweep of the isohyets of 40 and 35 inches towards the Great Haldon ridge south of Exeter.

The hills of East Devon between Honiton, Axminster, and Chard precipitate a relatively high rainfall, the isohyet of 40 inches including a large area which stretches into the eastern end of the Culm valley, and may possibly be found by additional observations to extend as a narrow neck to the wet area of Exmoor. Probably rainfalls as high as 45 inches will be found near Stockland, but the data do not permit of this being shown on the map. It appears that the very wet area on Dartmoor is elliptical in outline, with the long axis directed north and south; the smaller and less marked wet patch in the east is roughly circular in outline, and both of these lie practically outside the valley of the Exe so far as their influence on the volume of water reaching the river is concerned.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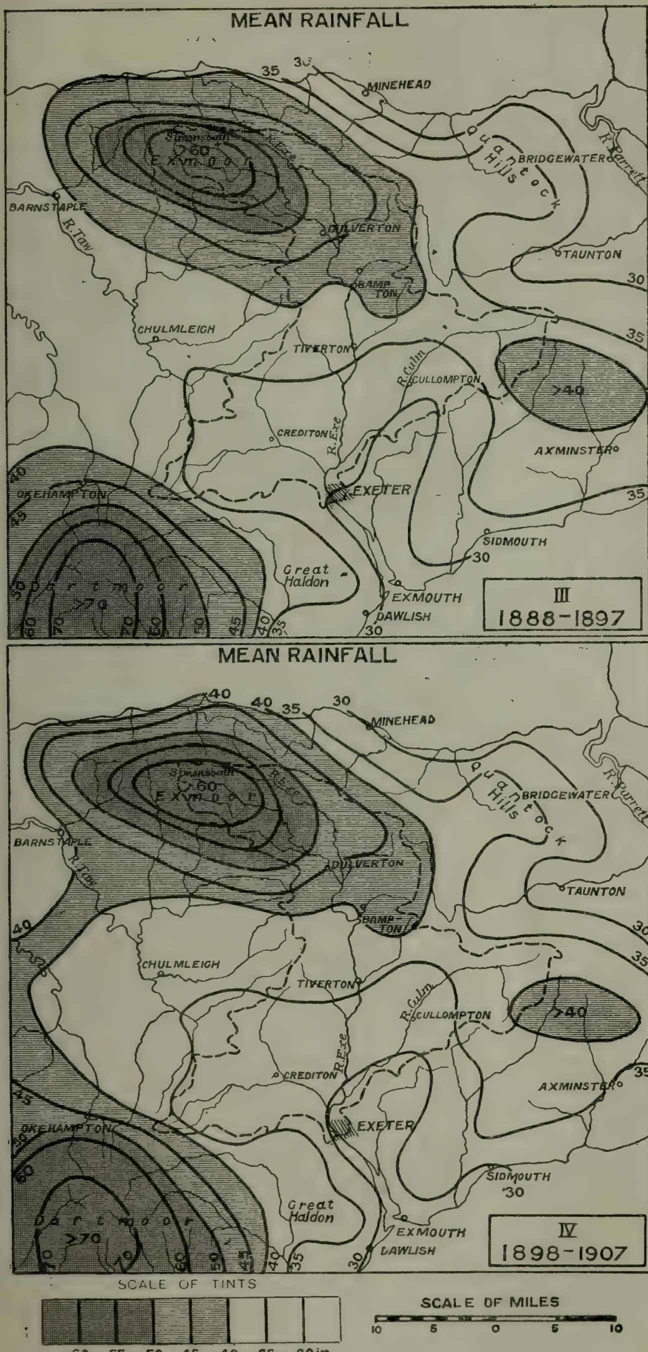
MINEHEAD
Simonsbath
Exmoor
>60
R. Exe
Quantock Hills
BRIDGEWATER
R. Parrett
BARNSTAPLE
R. Taw
DULVERTON
TAUNTON
BAMPTON
CHULMLEIGH
TIVERTON
R. Culm
CULLOMPTON
>45
CREDITON
AXMINSTER
EXETER
OKEHAMPTON
Dartmoor
>70
Great Haldon
SIDMOUTH
EXMOUTH
DAWLISH
I
1868-1877
MEAN RAINFALL
>40
II
1878-1887
SCALE OF TINTS
60 55 50 45 40 35 30in.
SCALE OF MILES
10 5 0 5 10


MEAN RAINFALL
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R. Culm
CULLOMPTON
>40
CREDITON
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OKEHAMPTON
EXETER
SIDMOUTH
Great Haldon
Dartmoor
>70
EXMOUTH
DAWLISH
III
1888-1897
MEAN RAINFALL
IV
1898-1907
SCALE OF TINTS
60 55 50 45 40 35 30in.
SCALE OF MILES
10 5 0 5 10

The third wet region dominates the Exe valley, and stretches in a long ellipse with the longer axis directed from west-north-west to east-south-east over Exmoor. The isohyet of 40 inches probably just reaches the northern corner of the Culm valley, crosses the Exe valley in an east-and-west direction midway between Tiverton and Bampton, and, sweeping far to the west, returns along the northern slope of Dartmoor to cross the south-western extremity of the Creedy valley. So far as the excellent, though rather scanty, records on Exmoor show, the wettest portion has somewhat more than 65 inches over about 8 square miles surrounding the source of the Burle, and the rainfall diminishes as the valley widens at the rate of about 5 inches in 3 miles for 12 miles down-stream, and then much more slowly. The Exe valley below Tiverton, and the whole valleys of the Culm and Creedy, belong to the central area of moderate rainfall, averaging about 37 inches, and are sheltered from all winds except those from north-west, south-east, and north-east by land that is substantially higher; but the drainage from one only out of the three intercepting high land-masses finds its way into the Exe. This fact considerably simplifies the *régime* of the river, which is dependent mainly on the heavy rains of Exmoor so far as its average flow is concerned.

The calculation of the total volume of water which falls as rain in an average year can be made from the average map in two separate ways. For convenience in dealing with two sets of mean values it is well to have two words to avoid confusion, and I have found it useful to use the word "average" for the mean of a long series of yearly values, and "general" for the mean at a large number of points uniformly distributed over a surface. Thus the general rainfall of the valley of the Exe is the mean depth at which the rain of a given period would stand, supposing it to remain as it fell without running off, evaporating, or percolating into the soil. The average general rainfall is the mean general rainfall for a long series of years. If the number of points from which an average rainfall map is constructed be sufficiently great, and sufficiently uniformly distributed, the mean of them all would give the average general rainfall of the area represented in the map. It usually happens, however, that a map has to be constructed, like those of the four decades for the Exe valley, from irregularly distributed points, the mean of which might be a totally misleading figure if used to represent the general rainfall. In such a case the general rainfall may be best obtained by measuring the areas between successive isohyets, multiplying each area by the general rainfall of the zone, which is either the mean of the two isohyets or some figure not greatly differing from the mean, which can readily be obtained by inspection, adding all those volumes together, and dividing by the total area. In the case of the average map of the Exe valley the calculation has been made in both ways, utilizing the points from which the map was constructed for the simple arithmetical computation, and measuring the areas between the lines with a planimeter on the quarter-inch map for the computation by zones.

The comparison of the two methods is shown in the following tables for each of the tributary basins and for the whole valley above Exeter, the terminal points of each basin being taken at the position where the river-gauges are fixed, so that a comparison with the stream-flow can be made when required :—

TABLE XIV.

Rainfall in the Neighbourhood of the River Exe.

Station.	Height above sea-level.	Duration of record.			Rainfall.				
		First year.	Last year.	No. of years.	Arithmetical mean.	Means for decades.*			
						I.	II.	III.	IV.
	feet.				ins.	ins.	ins.	ins.	ins.
Teignmouth, Woodway	235	1879	1890	12	33·59	—	34·80	30·90	—
,, Bonnicliff	260	1890	1907	18	31·46	—	—	31·60	31·24
Dawlish, Great Oak Park ...	120	1876	1889	14	35·78	36·90	35·66	31·20	—
Chudleigh, Ideford	300	1887	1907	21	33·87	—	36·10	34·31	34·44
Ilsington, Middlecott House ...	649	1868	1897	30	47·86	48·60	51·30	46·50	—†
Bovey Tracey, Colehays ...	415	1886	1907	21	44·56	—	48·90	44·99	46·40
,, ,, ...	93	1868	1884	17	45·93	46·26	43·40	—	—
Princetown	1360	1880 1886 1893 1896	1881 1889 1894 1907	20	76·55	—	76·20	76·90	78·33
,, Cowsic Valley ...	1352	1880	1907	28	72·37	—	78·10	73·74	68·26
Exmouth, Nidderdale	51	1893	1907	15	27·72	—	—	28·50	27·21
,, Mamhead	467	1892	1904	13	38·52	—	—	38·40	38·00
Torquay Water Works, Trusham	322	1885	1907	23	36·71	—	40·10	37·42	36·29
,, ,, ,, Tottiford	718	1881	1904	24	41·13	—	43·50	42·40	40·20†
,, ,, ,, Bullaton	928	1906	1908	3	37·77	—	—	—	42·30
,, ,, ,, Mardon	835	1904	1907	4	37·58	—	—	—	39·70
,, ,, ,, Kennick	842	1890	1907	18	40·38	—	—	40·97	39·62
Moretonhampstead	600	1902	1907	6	42·12	—	—	—	41·60
Chagford, Frenchbeare	950	1907	1908	2	52·50	—	—	—	56·60
,, Batworthy	1250	1885	1896	12	59·42	—	65·90	60·46	—
,, Dartmoor Sanatorium	750	1905	1908	4	43·24	—	—	—	47·80
Budleigh Salterton, Ravenshaw	50	1887 1901	1898 1902	14	28·55	—	30·70	29·86	29·20
,, ,, ...	80	1868	1890	23	32·34	35·40	32·70	29·60	—†
Kenton, Southtown House ...	56	1890	1907	18	33·36	—	—	33·50	34·00†
Powderham Castle	57	1875	1887	13	35·39	37·30	33·90	—	—†
Kenn, Chapel Court	126	1908	1908	1	25·52	—	—	—	33·70†
East Budleigh	70	1874	1890	16	33·78	35·40	33·81	30·60	—
,, ,, Bicton	90	1889	1907	19	29·76	—	—	30·20	29·63
Sidmouth, Sidmount	149	1870	1907	38	32·01	32·70	33·52	31·17	30·18
Topsham, Clyst St. George ...	76	1868	1884	17	33·65	33·73	32·60	—	—
Exeter, Ide	90	1907	1907	1	34·61	—	—	—	36·10
Seaton, White Cliff Glen ...	125	1871	1881	11	38·27	37·00	36·20	—	—†
Lyme Regis, Clevelands ...	465	1870	1907	38	35·18	37·35	36·44	34·48	32·42
Aylesbeare, Rosamondford ...	220	1904	1908	5	29·09	—	—	—	31·60
Exeter, St. Thomas	65	1902	1907	6	32·73	—	—	—	33·10
,, Manston terrace ...	165	1868	1904	37	32·06	35·84	32·20	29·11	29·20
,, Heavitree	175	1899	1906	8	31·51	—	—	—	30·80
,, St. Leonard's road ...	110	1883 1886	1884 1889	6	29·80	—	32·80	31·60	—
,, Lyndhurst road ...	140	1891	1894	4	31·25	—	—	30·60	—
,, D. & E. Institution ...	155	1868	1907	40	31·55	34·80	32·30	29·48	29·63
,, Elmfield	100	1899	1907	9	28·22	—	—	—	28·60†
Cheriton Bishop	575	1907	1908	2	29·62	—	—	—	32·40
Okehampton, Oaklands	500	1870	1907	38	46·95	50·29	47·66	45·10	44·85
Spreyton	735	1903	1908	4	33·82	—	—	—	34·10
Broad Clyst, Brockhill	80	1878 1882	1879 1907	28	29·38	—	31·00	29·10	28·41
Newton St. Cyres...	145	1904	1908	5	28·43	—	—	—	31·50
Upton Pyne	213	1903	1907	5	33·23	—	—	—	33·10
Brampford Speke...	140	1868	1891	24	35·19	36·91	34·51	31·70	—
Crediton, Newcombes	251	1904	1906	3	32·02	—	—	—	34·40
,, Okefield	325	1905	1908	4	28·04	—	—	—	32·50
Silverton, Killerton	161	1904	1907	4	27·10	—	—	—	28·50†
Kilmington, Haddon Corner ...	400	1904	1908	5	34·36	—	—	—	35·50
Axminster...	138	1882	1893	12	35·24	—	39·00	35·50	—†
Honiton, Gittisham	—	1868	1883	16	41·16	40·84	39·30	—	—
,, Feniton Court... ...	229	1889	1892	4	32·51	—	—	33·90	—
,, St. Cyrus	—	1907	1907	1	36·51	—	—	—	35·90
,, Ivedon	430	1889	1900	12	32·59	—	—	33·69	31·80
,, Combe Raleigh ...	500	1902	1907	6	36·90	—	—	—	36·60
Hatherleigh, Broomford Manor	484	1882	1897	16	40·94	—	43·00	39·67	—†
Zeal Monachorum	600	1870	1879	10	41·63	41·11	40·90	—	—
Stockleigh Pomeroy	340	1895	1907	13	32·84	—	—	32·20	33·01

* Decade I. = 1868–1877; II. = 1878–1887; III. = 1888–1897; IV. = 1898–1907.

† A slight correction has been applied at this station, on account of the height of the rain-gauge above ground considerably exceeding 1 foot.

Station.	Height above sea-level.	Duration of record. First year.	Last year.	No. of years.	Rainfall. Arithmetical mean.	Means for decades.* I.	II.	III.	IV.
	feet.				ins.	ins.	ins.	ins.	ins.
Clyst Hydon	200	1868	1880	13	33·97	34·47	31·70	—	—
Bradninch, Strath Culm... ...	159	1868	1882	15	33·91	33 93	31·80	—	—
,, ...	250	1868	1873	6	35·08	38·00	—	—	—
,, Vicarage	316	1877	1887	11	37·07	41·10	36·26	—	—
Broadhembury	400	1868	1873	6	33·68	35·50	—	—	—
Chard, Tatworth	347	1902	1907	6	41·91	—	—	—	40·40
,, Cricket St. Thomas ...	400	1868	1907	40	39·72	44·15	39·59	38·59	36·51
Cullompton	202	1881	1907	27	34·29	—	36·24	33·72	33·72
Dunkerswell Abbey	800	1907	1908	2	35·42	—		—	39·10
Heanton Satchville	332	1885	1907	23	37·98	—	42·80	37·89	37·77
Dolton, Hilliers	380	1907	1908	2	33·41	—	—	—	36·70
Chulmleigh, Eggesford	400	1871	1877	7	42·21	40·20	—	—	—
Witheridge	600	1891	1894	4	39·77	—	—	38·30	—
Tiverton, Rose Bank	280	1876	1887	12	41·33	39·50	42·29	—	—
,, Highfield	450	1903	1907	5	41·60	—	—	—	40·60
,, Broomhill	380	1883 1897	1894 1907	23	36·96	—	41·00	37·30	35·54
,, Ivy Place St. Peter's Street ...	270	1880	1907	28	36·56	—	40·90	37·70	37·40†
,, Exe Villa	230	1873	1878	6	42·95	39·80	39·40	—	—
,, Springfield	300	1868	1875	8	41·13	43·00	—	—	—
Halberton	240	1906	1908	3	31·47	—	—	—	34·00
Uffculme, Bullmoor	280	1902	1907	6	34·21	—	—	—	34·20
Tiverton, Chevithorne	510	[illegible]	1873	2	47·56	40 50	—	—	—
Loxbear	—	1874	1874	1	34·76	34·20	—	—	—
Otterford, Otterhead	735	1894	1903	10	39·17	—	—	37·50	37·60
Churchstanton	800	1882	1884	2	41·75	—	39·50	—	—
Blagdon Hill reservoir	588	1894	1907	14	35·78	—	—	33·90	35·89
Leigh Hill reservoir	525	1894	1907	14	34·45	—	—	33·00	34·42
,, Court	350	1902	1907	6	34·04	—	—	—	33·30
Torrington, Little Silver ...	400	1877 1892	1890 1907	30	41·18	42·70	43·82	38·98	40·06
,, Stevenstone ..	420	1880	1907	28	41·13	—	43·50	39·65	41·03
Rackenford, Cruwyshaye ...	400	1894	1894	1	46·65	—	—	40·60	—
Meshaw	472	1868	1877	10	41·99	41·99	—	—	—
Romansleigh	590	1900	1906	7	37·89	—	—	—	37·10
Rose Ash	650	1870	1894	25	40·55	43·24	39·28	38·30	—
Bampton, Cove	450	1868	1887	20	42·90	44·41	41·40	—	—
Huntsham Court	640	1874	1907	34	45·21	47·30	45 62	44·66	42·45
Wellington, The Avenue ...	254	1893	1906	14	30·85	—	—	30·30	30·40
,, Windwhistle House	300	1894	1896	3	32·90	—	—	31·70	—
,, Sunnyside	—	1880 1890	1887 1894	12	32·41	—	32·20	32·90	—
Bampton, Wonham	530	1898	1907	10	39·23	—	—	—	39·23
,, ...	400	1868	1871	4	39·46	45·70	—	—	—
Exebridge	400	1908	1908	1	35·68	—	—	—	42·60
Chittlehambolt	500	1903	1904	2	44·43	—	—	—	38·20
Taunton, Gatchell House ...	160	1907	1907	1	29·88	—	—	—	28·90
,, Claremont	80	1891	1901	11	27·34	—	—	27·20	26·50
,, Linden Grove	70	1900	1907	8	27·59	—	—	—	27·30
,, Ashleigh	78	1900	1907	8	26·82	—	—	—	26·60
,, ...	80	1893	1894	2	28·26	—	—	26·40	—
,, Fullands School ...	—	1868	1883	16	29·63	29·40	28·20	—	—
Milverton, Olands	330	1903	1906	4	34·79	—	—	—	34·20
,, The Nook	265	1898	1904	7	33·49	—	—	—	32·00
,, The Lodge	198	1880	1897	18	34·66	—	37·36	33·33	—
,, Spring Grove ...	500	1897	1907	11	35·40	—	—	34·30	35·04
Taunton, Staplegrove	108	1902	1905	4	30·59	—	—	—	29·60
Norton FitzWarren	140	1888	1894	7	31·59	—	—	32·00	—
Wiveliscombe, Wythycombe House	800	1878	1883	6	42·30	—	39·60	—	—
Wiveliscombe	—	1868	1881	14	36·27	36·75	34·30	—	—
Halse, The Mount	254	1894 1906	1903 1907	12	33·64	—	—	32·60	32·10
,, Rectory	245	1877	1882	6	36·33	34·30	33·30	—	—
,, ...	200	1884	1891	8	30·20	—	33·50	30·40	—
Fitzhead	297	1880 1886	1884 1890	10	34·31	—	37·00	33·10	—
South Molton, East Street ..	430	1874	1902	29	43·44	45·60	44·32	42·54	40·30
,, ,, ...	450	1903	1907	5	46·43	—	—	—	44·90

* Decade I. = 1868–1877; II. = 1878–1887; III. = 1888–1897; IV. = 1893–1907.

† A slight correction has been applied at this station, on account of the height of the rain-gauge above ground considerably exceeding 1 foot.

Station.	Height above sea-level.	Duration of record. First year.	Duration of record. Last year.	No. of years.	Rainfall. Arithmetical mean.	Means for decades.* I.	II.	III.	IV.
	feet.				ins.	ins.	ins.	ins.	ins.
South Molton	515	1894	1900	7	43·66	—	—	44·10	41·50
,, ,, Castle Hill school	363	1890	1907	18	42·35	—	—	42·10	42·27
,, ,, ,, gardens	317	1868 / 1899	1893 / 1907	35	44·24	49·00	45·00	43·50	43·40†
East Anstey	740	1906	1908	3	42·85	—	—	—	45·80
Skilgate	750	1876	1882	7	51·13	46·60	46·10	—	—
Molland	674	1906	1908	3	49·11	—	—	—	52·60
West Buckland Rectory ...	—	1889	1889	1	40·60	—	—	44·50	—
,, ,, County school	650	1884	1888	5	43·86	—	48·10	44·60	—
Barnstaple	31	1868	1907	40	38·10	42·05	41·26	33·14	35·94
Winsford	630	1897	1907	11	50·30	—	—	47·40	49·91
Cothelstone House	500	1875	1907	33	35·49	37·00	36·12	35·91	32·29
North Petherton	122	1899	1907	9	29·82	—	—	—	29·50
Enmore Park	268	1895	1901	7	31·45	—	—	33·00	30·30
Bridgwater	30	1888	1907	20	27·79	—	—	28·28	27·31
Stoke Rivers	767	1906	1908	3	44·02	—	—	—	44·70
Bratton Fleming	—	1898	1898	1	48·83	—	—	—	52·60
Exford Rectory	905	1875	1890	16	54·10	56·80	54·25	47·10	—
,, North Ley	1000	1904	1907	4	42·57	—	—	—	46·90†
Simonsbath	1080	1899	1907	7	69·07	—	—	—	66·50
Challacombe	825	1901	1907	7	63·86	—	—	—	63·40
Arlington Court	613	1871	1907	37	54·08	55·15	53·68	51·02	54·24
Williton, Aller Farm	190	1904	1907	3	30·31	—	—	—	33·80†
Holford, Woodlands House ...	391	1895	1907	13	32·83	—	—	33·60	32·70
Watchett, Old Cleeve	200	1885	1885	1	38·15	—	39·90	—	—
Quantockshead, St. Audries ...	250	1898	1907	10	28·04	—	—	—	28·04
Pawlett	45	1895	1904	10	28·28	—	—	29·00	27·70
Stockland Bristol	65	1898	1907	10	27·95	—	—	—	27·95
Dunster, Knowle	267	1889	1895	7	35·10	—	—	35·00	—
,, The Priory	150	1874	1881	8	36·94	37·10	32·70	—	—
,, Alcombe	85	1901	1906	6	29·28	—	—	—	29·40
Minehead, Blair	75	1889	1891	3	28·89	—	—	29·40	—
,, ...	50	1895	1899	5	31·02	—	—	30·60	32·90
,, Mariansleigh ...	45	1905	1908	4	27·39	—	—	—	30·30
Parracombe	795	1888	1907	20	47·07	—	—	46·00	50·00†
Porlock	175	1877	1883	4	52·51	50·50	48·00	—	—
Allerford, Lynch Mead	100	1907	1907	1	31·06	—	—	—	32·40
Porlock, Bossington	44	1904	1906	3	30·49	—	—	—	32·30
,, Ashley Combe	200	1884	1888	4	42·24	—	48·20	40·10	—
Lynmouth, Glenthorne	93	1874	1900	27	45·16	49·40	45·78	41·47	46·10
Martinhoe	808	1874 / 1898	1878 / 1907	14	46·73	52·60	44·00	—	44·90†
Lynton, Lee Abbey	320	1878	1907	34	38·10	43·70	37·97	35·18	38·05
,, Gwynallt	284	1894	1907	10	43·01	—	—	—	43·01
Lynmouth, Rock House ...	20	1898	1907	10	39·95	—	—	—	39·95
Burnham	18	1868	1880	13	30·26	29·80	—	—	—

Table XV.—Mean Annual Rainfall of Exe Valley, 1868–1907.

River-basin.	Area sq. miles.	Map I. 10 yrs. 1868–77.	Map II. 10 yrs. 1878–87.	Map III. 10 yrs. 1888–97.	Map IV. 10 yrs. 1898–07.	Map V. 40 yrs. 1868–1907.
		in.	in.	in.	in.	in.
Exe, below Brampford Speke	9·1	36·2	33·5	30·9	30·0	32·5
,, above ,, ,,	241·5	49·7	48·3	44·8	45·0	47·0
,, whole	250·6	49·3	47·8	44·3	44·5	46·4
Culm, below Silverton ...	6·5	34·8	34·1	32·0	30·1	32·5
,, above ,, ...	101·8	39·5	37·8	35·4	35·0	37·0
,, whole	108·3	39·2	37·6	35·2	34·7	36·7
Creedy ,, ...	102·0	39·3	36·6	33·8	33·8	36·1
Exe, above Exeter (by map)	460·9	**44·7**	**42·9**	**39·9**	**39·8**	**41·8**
,, ,, ,, (by 77 points)		44·8	43·2	39·8	40·2	42·0

* Decade I. = 1868–1877; II. = 1878–1887; III. = 1888–1897; IV. = 1898–1907.

† A slight correction has been applied at this station, on account of the height of the rain-gauge above ground considerably exceeding 1 foot.

The areas given in the table are the means of the planimeter measurements on the five maps, which were separately measured on the scale of 4 miles to an inch; they are merely convenient working figures, not to be taken as of high accuracy. Where exact measurements are required, the precise determinations of area from the large-scale maps will of course be used.

Table XVI. compares the areas of the zones between successive isohyets in the Exe Valley as a whole, *i.e.* above Exeter, for each of the decades and for the whole period of forty years.

TABLE XVI.—AREAS OF EXE VALLEY WITH RAINFALL OF DIFFERENT AMOUNTS IN SUCCESSIVE DECADES AND ON THE AVERAGE OF FORTY YEARS.

Period.	Below 30 ins.	30–35 inches.	35–40 inches.	40–45 inches.	45–50 inches.	50–55 inches.	55–60 inches.	Above 60 ins.	Whole Exe Valley.
	sq. miles.	sq. miles.	sq. miles.	sq. miles.	sq. miles.	sq. miles.	sq. miles.	sq. miles.	sq. miles.
1868–1877	—	10·5	187·6	110·3	40·0	19·3	64·0	29·2	460·9
1878–1887	—	60·6	176·3	87·8	34·9	50·9	19·6	30·8	460·9
1888–1897	6·6	169·2	105·5	82·0	46·1	17·2	15·1	19·2	460·9
1898–1907	13·2	172·5	114·4	61·9	34·7	25·4	13·1	25·7	460·9
1868–1907	—	86·9	184·4	70·9	35·6	36·9	20·4	25·8	460·9

Both tables agree in showing a diminution of rainfall and an increase of the area with lower rainfalls from the earlier to the later decades; but before entering upon the question of the changes in rainfall with time, we should consider the average condition, which must be taken as a basis for comparison.

The average rainfall of the Exe Valley, as shown on the map for the forty years 1868–1907, is nowhere less than 30 inches; but 271·3 square miles have a rainfall less than 40 inches, 106·5 square miles a rainfall between 40 and 50 inches, and 83·1 square miles a rainfall greater than 50 inches; the general rainfall for the whole area being 41·8 inches, or, to use the convenient round number, 42 inches. An inch of rain over 1 square mile is equal to 14,479,000 gallons of water; hence 41·8 inches over 460·9 square miles is equal to 280,281·6 million gallons per annum, or to an average daily volume of 768 million gallons. Although this volume of water falls upon the Exe Valley, the amount carried off by the river must be less by the amount evaporated or percolating through the ground below the bed of the stream. It is one of the main objects of the work of the committee to determine what that amount may be; but a common assumption is that it is something in the neighbourhood of 16 inches, and, if that be so, the annual flow of the river should be about 173,508 million gallons, and the average daily flow at Exeter about 475 million gallons, *i.e.* 19,790,000 gallons per hour, or 882 cubic feet per second. As the cross-section of the river at Exeter at mean level is 1204 square feet, it follows that the mean velocity of the stream, if the assumed evaporation is correct, would be 2640 feet, or half a mile per hour.

From Table XV. the proportion of the total volume of water falling on each of the three main basins can readily be calculated, and this is expressed in the convenient units of square-mile-inches in Table XVII., and in the form of a percentage of the whole volume in Table XVIII. The latter table shows that, while each of the three subordinate basins did in some decades contribute a slightly larger, and in others a slightly smaller, proportion of the whole volume of rainfall, the variation was not great, and never deviated appreciably from the proportions shown by the 40-years' average, viz. 60·4 per cent. for the Exe, 20·6

for the Culm, and 19 per cent. for the Creedy. Speaking roughly, the Culm and Creedy receive an equal volume of rainfall over their basins, and the Exe three times as much as either, the Exe being the preponderating partner to the extent of 3 to 2.

TABLE XVII.—VOLUME OF MEAN ANNUAL RAINFALL OF EXE VALLEY, 1868–1907.

River-basin.	Map I. 10 years 1868–87.	Map II. 10 years 1878–87.	Map III. 10 years 1888–97.	Map IV. 10 years 1898–07.	Map V. 40 years 1868–07.
	sq. mile-in.	sq. mile-in.	sq. mile-in.	sq. mile-in.	sq. mile-in.
Exe below Brampford Speke...	330	300	280	270	290
,, above ,, ,, ...	12,020	11,670	10,840	10,870	11,330
,, whole	12,350	11,970	11,120	11,140	11,620
Culm below Silverton	220	220	210	200	210
,, above ,, ...	4,020	3,850	3,610	3,560	3,760
,, whole	4,240	4,070	3,820	3,760	3,970
Creedy	4,010	3,730	3,450	3,440	3,680
Exe above Exeter (by map) ...	20,600	19,770	18,390	18,340	19,270

TABLE XVIII.—PERCENTAGE VOLUME OF MEAN ANNUAL RAINFALL OF EXE VALLEY, 1868–1907.

River-basin.	I. 1868–77.	II. 1878–87.	III. 1888–97.	IV. 1898–07.	V. 1868–07.
Exe below Brampford Speke ...	1·6	1·5	1·5	1·5	1·5
,, above ,, ,, ...	58·4	59·0	59·0	59·2	58·8
,, whole	60·0	60·5	60·5	60·7	60·3
Culm below Silverton	1·1	1·1	1·1	1·1	1·1
,, above ,, ...	19·5	19·5	19·6	19·4	19·5
,, whole	20·6	20·6	20·7	20·5	20·6
Creedy	19·4	18·9	18·8	18·8	19·1
Exe above Exeter	100·0	100·0	100·0	100·0	100·0

Table XIX. takes the volume of the total precipitation of the average of forty years as 100, and expresses the proportional volume of rainfall of each of the three tributaries as percentages.

TABLE XIX.

	I. 1868–77.	II. 1878–87.	III. 1888–97.	IV. 1898–1907.	V. 1868–1907.
Exe	106	103	95	95	100
Culm	107	102	96	95	100
Creedy	109	101	94	94	100
Total	107	103	95	95	100

This shows that the first two decades dealt with had a general rainfall respectively 7 and 3 per cent. above the average, the last two 5 per cent. below the average, for the forty years. From the first three decades it would appear that the rainfall was steadily diminishing, but the fourth decade shows that the diminution had ceased. There is no doubt that all over the British Isles there was a spell of

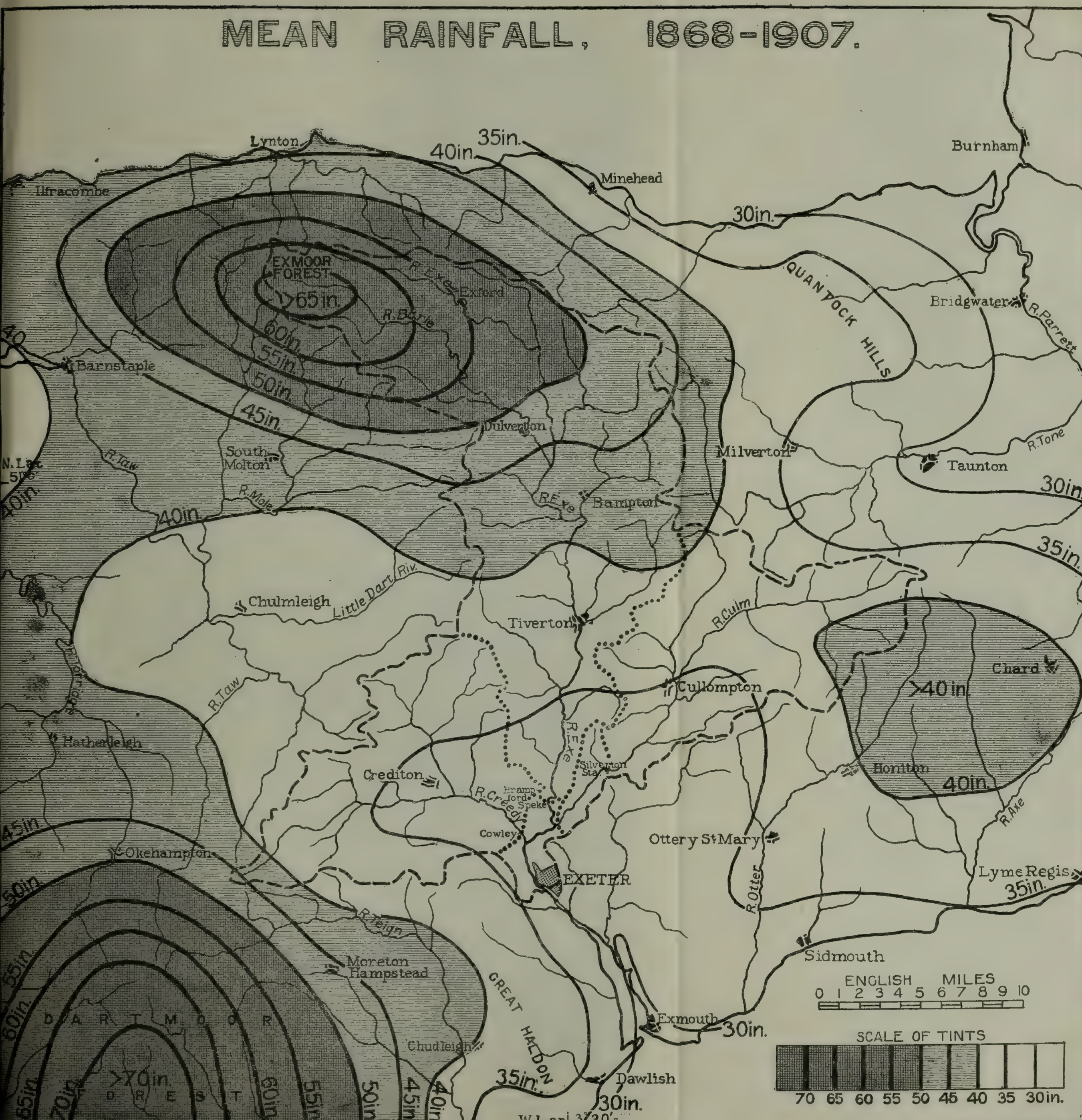
very wet years in the late seventies and early eighties, and a spell of drier years in the nineties of last century, but there is no reason why another spell of wet years should not be expected to preserve the balance.

The variations from one year to another are of course much greater than the variations of the mean of consecutive decades, but in the absence of a large number of stations running through the whole period, they are not so easy to ascertain. The method we have adopted in order to overcome the deficiency of short records is as follows. There are for each of the larger tributary basins several records which run through a whole decade, and a sufficient number of these is selected to give a representative distribution. The percentage which each year's rainfall forms of the ten-year mean at that station is calculated, and the mean percentage at all the stations for each year is taken as representing the mean of the basin. This is done for each decade, and these percentages are then corrected to a common standard. This is done by taking the percentage which the general rainfall for each decade as determined from the maps makes of the average general rainfall taken from the combined map for forty years, and re-calculating the years of each decade so that, while preserving the same ratios *inter se*, they yield a mean equal, not to 100, but to the percentage greater or less than 100 which the decade forms of the general mean. All the figures then express percentages of the average general rainfall, and they are given in Table XX. for each of the three divisions, and for the Exe valley as a whole. In calculating the general ratios for the valley as a whole, the ratios of the Exe above Brampford Speke have been given twice the weight of the other tributaries in accordance with the area of its valley.

TABLE XX.—FLUCTUATION OF ANNUAL RAINFALL IN THE EXE VALLEY, 1868–1907.

Year.	Exe Valley.	Culm Valley.	Creedy Valley.	Whole Exe Valley.
1868	103	108	107	105
1869	99	94	101	98
1870	68	71	74	70
1871	94	96	101	96
1872	137	140	140	139
1873	95	94	99	96
1874	103	101	108	104
1875	120	120	120	120
1876	119	124	123	121
1877	122	120	122	121
1878	109	109	105	108
1879	102	105	103	103
1880	107	102	104	105
1881	99	103	101	101
1882	135	129	129	132
1883	105	106	106	105
1884	89	87	90	89
1885	99	103	103	101
1886	111	113	110	111
1887	73	68	68	71
1888	98	104	100	100
1889	82	81	83	82
1890	88	90	91	89
1891	112	113	109	111
1892	82	80	82	81
1893	92	89	86	90
1894	111	114	111	112
1895	98	99	97	98
1896	81	80	78	80

MAP V.



AVERAGE ANNUAL RAINFALL OF THE EXE VALLEY AND SURROUNDING COUNTRY.

[To face page 48.

FLUCTUATION OF ANNUAL RAINFALL IN THE EXE VALLEY.

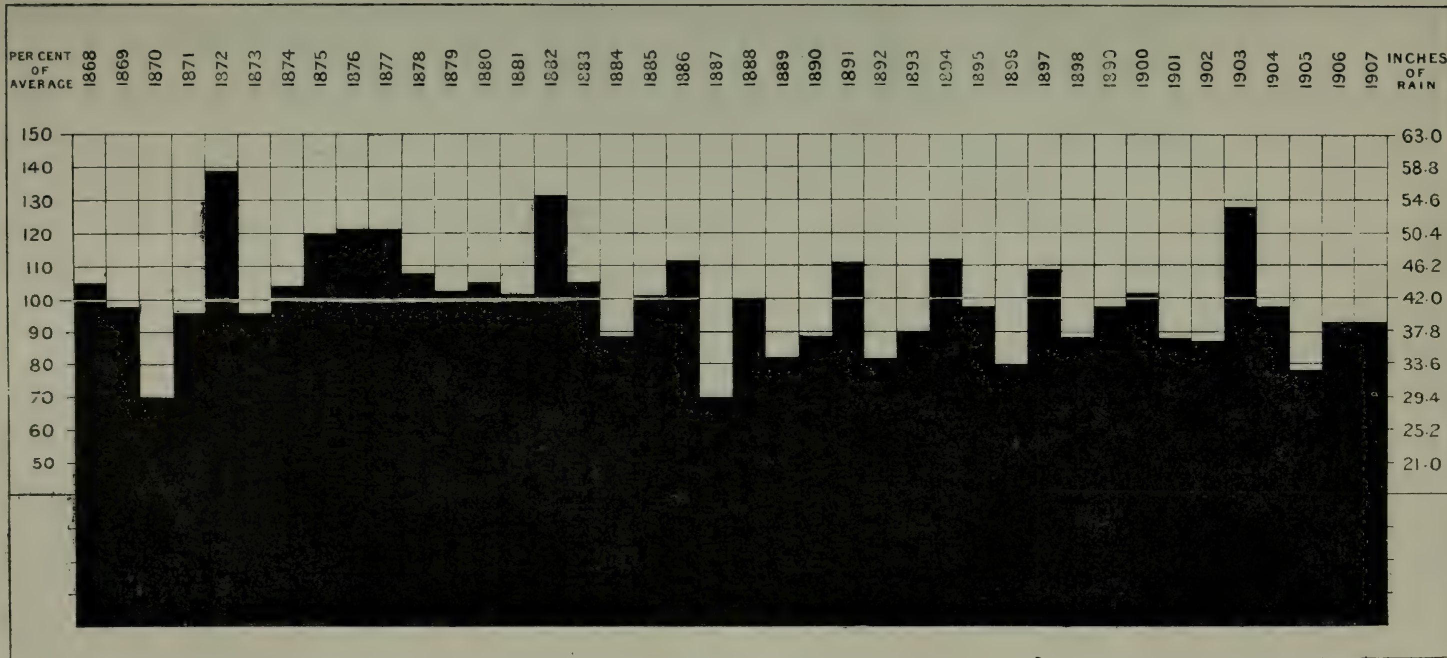


FIG. 8.

Year.	Exe Valley.	Culm Valley.	Creedy Valley.	Whole Exe Valley.
1897	109	111	107	109
1898	90	85	89	88
1899	97	96	99	97
1900	104	100	98	102
1901	87	89	88	88
1902	86	89	86	87
1903	130	128	123	128
1904	97	97	100	98
1905	78	78	78	78
1906	97	90	87	93
1907	92	94	94	93
Average	100	100	100	100

The final result is given in graphic form in the diagram, Fig. 8, where the black columns show the relative total rainfall of the individual years from 1868 to 1907, the average line being ruled through horizontally at 100. The diagram is graduated on one side in percentages of the average, and the approximate equivalents in inches, taking the average as 42 inches, are added on the other side.

The relations as brought out by this diagram are extremely interesting, the more so as the form is exactly similar to that of diagrams constructed for other large areas in the British Isles * and for individual stations in most parts of the country. The variations represented cannot be viewed as local; but, on the other hand, our present knowledge does not justify us in saying that there may not be differences in the phase and amplitude of the deviations between one part of Great Britain and Ireland and another.

In the Exe valley the years 1870 and 1887 were the driest, 1870 appearing here to have been slightly drier than 1887, though in most parts of the British Isles the driest year was 1887.† Between those two very dry years there were only two which fell below the average, and these only by a little. From 1874 to 1883 there were ten consecutive years all of which were above the average, and the mean rainfall of these ten years was 12 per cent. above the average. From 1888 to 1905 there were, as in most parts of the British Isles, six recurrences of groups of three years, one of which had more and the two following less than the average rainfall. The remarkable uniformity of this repeated sequence of one wet year followed by two dry years cannot be due to chance, but suggests a definite cycle of meteorological changes with a period of very nearly three years. The fact that this periodicity was not apparent before 1888 prepares one for its disappearance, and that appears to have resulted in 1906. It is difficult to imagine any set of conditions which suddenly came into existence in 1888 and suddenly ceased eighteen years later, so that we are compelled to view the three-year period as a physical fact, changes being due to the period being really different from three years by a small fraction, or to the superposition of some other recurring change of different period. It is evident that by taking the ten-year groups with which we have been

* See Water-supply Memoirs of the Geological Survey for Lincoln, Suffolk, Yorkshire (East Riding), Northampton, and Bedford, Oxford, Kent, Sussex, Hampshire. (Some of these are not yet published. 1909.)

† See H. R. Mill, "The Mean Rainfall of the British Isles," *Min. Proc. Inst. C.E.*, vol. 155 (1903-4), pt. i.

dealing, we have obtained the impression of a progressive diminution of rainfall, the periods running—

107, 103, 95, and 95 per cent. of the average.

By commencing in 1872 the first three ten-year periods would be even more eloquent of a progressive drying-up of the country—

112, 99, 94 per cent. of the average.

Dividing the whole into eight groups of five years each, we have the means—

102, 112, 110, 95, 93, 98, 92, 98 per cent. of the average,

and dividing it into ten periods of four years each, we have the successive figures—

92, 115, 113, 111, 93, 95·5, 95·5, 93·5, 101, 93 per cent. of the average.

Finally, taking three-year periods, they run—

	91	110	115	111	113	98	94	94	94	96	96	101	90
or	88	113	121	105	113	100	84	94	100	92	96	104	88

according as the first year or the last year is omitted to make the series complete.

Viewed in all these various groupings, the very high rainfalls of the years from 1872 to 1886 appear to be abnormal features, following a succession of years with much lower rainfall, and followed in turn by a succession of years with lower rainfall. Trustworthy records do not go far enough back to enable us to judge whether a recurrence of a long series of wet years is to be expected in the early future; but they are sufficient to show that the diminution of rainfall is not progressive, but that even the three-year groups tend to recur in a succession of one wet followed by two dry, suggesting a nine-year period superimposed on the three-year period.

The four periods of nine years each, from 1870 to 1905, have the mean values 108, 102, 94, 97 per cent. of the average, showing a distinct recovery from the lowest values, and suggesting that the following nine-year period might rise above the average again. In any case, we can see no reason for supposing that there is a progressive diminution of annual rainfall, though a comparatively dry spell has succeeded a comparatively wet spell.

REPORT ON THE DAILY RAINFALL OF THE EXE VALLEY DURING THE YEARS 1907–1912.

By HUGH ROBERT MILL, D.Sc., LL.D.

The foregoing Report described the method of obtaining a map of the general rainfall over a large area, and gave a discussion of the fluctuation of annual rainfall in the Exe valley from 1868 to 1907. So far as it went this was a complete and final treatment of the subject, and I now add the figures representing the fluctuations of rainfall in the three valleys for the years 1907 to 1912. These are set out in Table XXII., and may be taken as supplementing the previous paper. The problem to be dealt with in the present report is the determination of the general

rainfall for the river valley for each day, and for this we are dependent upon such rainfall records as are taken daily, the accuracy and comparability of these depending not only on the care of the observer in making the exact measurements, but on his visiting the rain gauge at the same hour daily, and on his complying with the regulation for reading the rain gauge at a standard hour, 9 a.m. It is obvious that, when rain is falling, the fact of visiting the rain gauge too late has the effect of giving too much rain to one day and too little to the next.

In the valley of the Exe and its tributaries or on its borders there were about thirty-five stations for each year at which daily rainfall was measured, and it might appear at first that the utmost that could be done would be to take the average of the readings at all these stations for each day. This would have been a perfectly satisfactory method if the stations had been distributed at equal intervals over the whole area; but, as a matter of fact, they were very irregularly placed, so that the average of the whole would have given undue weight to the rainfall of certain districts, and, if these happened to be the wettest or the driest parts of the area, the difference from the general fall for a day would be very considerable. In order to overcome this difficulty, a certain number of stations was selected, so as to give the nearest possible approach to uniform grouping. When this was done, it was possible to utilize twenty stations, the mean of which might be trusted to give a fair approximation to the general rainfall of the area. It was necessary, however, to adopt some method of checking these results, and, after much consideration, the following procedure was adopted, which, although the amount of labour involved was very great, I feel confident ensures the best possible result. As there were only two river gauges at work during the period, I have thought it unnecessary to separate the volume of rain falling on the valleys of the Creedy and Culm, but have grouped the results as "the Exe valley above Brampford Speke" and "the Exe valley above Exeter," the latter of course including the former.

The first step in the process was to prepare an annual map showing by isohyetal lines the whole rainfall for each year. These maps were measured, and the volume of rain determined in the manner described in my former paper: and, as there was a much larger number of stations available for the whole year, the determination of the total volume is of a higher degree of accuracy than the determination of the volume of rain for a single day. The accuracy of the annual determinations is further assured by the fact that the general distribution of rainfall in any one year is similar in its broad lines to the average distribution, and there is thus a guide in drawing isohyetals across thin places on the map, which is not available in the case of monthly or daily values, when the distribution may vary very widely from its normal arrangement. The second step was to draw maps of the rainfall of each month, which were possibly slightly less accurate than the annual maps on account of the less degree of certainty in drawing the isohyets across thin places. The volume of the rainfall for each month was determined by measurements on the map, and it will be observed, on comparison of these values derived from the map with the means of twenty stations, that there were occasionally considerable differences. The map values are to be preferred on account of the facility afforded by the map for detecting and allowing for anomalous readings, which may be due either to errors of observation, or to local variations of such exceptional character as to be almost regarded as accidental. The volume of rainfall having been determined for each month, the total amount should add up to that as determined on the annual map. As a matter of fact, there was always some difference, and, the annual map being for the reason stated held to be more accurate than the monthly maps, the difference between the two was distributed proportionally throughout the months, so as to make the total of the monthly volumes equal to the annual. The difference

rarely exceeded one-tenth of an inch in any month. The monthly totals so adjusted can thus be viewed as the closest possible approximation to the truth.

The next step consisted in calculating the mean of the readings at the twenty selected stations for each day. The total of these means for each month was then compared with the general rainfall as deduced from the adjusted map-values for that month. Here, as was to be anticipated, the differences, though not great, were more irregular, and the first step which was taken was to draw a map of the rainfall on each day on which there was any appreciable area yielding a fall exceeding one inch, or on which there was a considerable fall the distribution of which varied in marked degree from the distribution of rainfall in a normal month. There were thirty-two cases of this kind in the sixty-three months. The rainfall zones on each map were measured, and the rainfall for the day calculated accordingly. The rainfall of these wet days showed remarkable variation in distribution. Sometimes the distribution was similar to that of a normal month ; but in other cases the part of the area normally the driest had the heaviest fall, and the wettest districts, such as Exmoor, had the least rainfall for the day. It so happened frequently that, of the ten stations representing the rainfall above Brampford Speke, more than half lay in the drier part of the area, so that the numerical mean gave a figure below the true general fall. It happened just as often that the greater number of stations lay within the wetter area, so that the figures gave a higher value than the true general rainfall. The map-values were adopted in each case, and the means for the remaining days were corrected proportionally, so as to bring the total to correspond with that for the month, which, in turn, had been checked by that for the year. The amount of the correction of the daily values was almost always within the error of observation, as the mean values had been computed to three places of decimals, whilst the observations are given to only two places. The figures for the valley of the Exe above Brampford Speke, and for the valley of the Exe above Exeter, including the Creedy and the Culm, are set out in the tables.

The work of making these calculations was very heavy. It involved, in the first instance, the copying out of the daily values for 2005 monthly records of rainfall, and a minute study of the returns to make sure that no cases of entering to a wrong day had been overlooked when preparing the figures for publication in *British Rainfall.* At the same time the opportunity was taken of comparing the readings for each day at all the stations more minutely than was possible when dealing with the whole country in the annual volumes of *British Rainfall.* Some minor errors were thus detected, and a few corrections were made for occasional failure to measure snowfall.

The changes in the annual totals published in *British Rainfall* necessitated by these corrections are as in Table XXI.

The two instances in which corrections of a greater magnitude than 1 inch were made occurred at Simonsbath, the station of highest rainfall, where very heavy daily falls are common, and there are few neighbouring stations by which they could be checked. After correspondence with the Observer it was ascertained that both cases were due to misplacing the decimal point in entering the rainfall. Every case in which an alteration was necessary was found to have occurred in the absence of the Observer, when the gauge was left in less skilled hands.

Maps were plotted for the six individual years and the sixty-three separate months, and also for 32 of the wettest days, a total number of 101 maps on a scale of 8 miles to 1 inch. The areas between all the isohyetal lines on each map were then measured, the mean rainfall of the zones determined by inspection and the volume of water calculated in square-mile-inches. The sum of all the volumes divided by the total area gave the general rainfall.

TABLE XXI.

Date.	Station.	Altitude.	Rainfall as published.	Rainfall as corrected.
		Feet.	Inches.	Inches.
1907	Cheriton Bishop	575	34·41	34·22
,,	Bampton (Huntsham)	640	39·18	39·43
,,	Molland	674	48·34	47·84
,,	Leigh Court	350	34·85	34·25
,,	Milverton (Spring Grove) ...	500	33·16	33·66
1908	Cheriton Bishop	575	24·76	24·29
,,	Brampford Speke...	83	21·29	21·79
,,	Stockleigh Pomeroy	340	26·34	26·16
,,	Tiverton (St. Peter-st.)	270	28·76	28·45
,,	East Anstey	740	40·07	40·36
,,	Simonsbath	1080	61·30	58·51
1909	Cheriton Bishop	575	30·74	31·49
,,	Brampford Speke	83	28·82	29·12
,,	Tiverton (Blundell's School) ...	265	35·81	35·00
,,	Bampton (Huntsham)	640	36·65	37·40
,,	Spreyton Vicarage	735	29·28	30·03
,,	Molland	674	45·95	46·70
,,	Challacombe	855	62·60	62·00
1910	Cheriton Bishop	575	47·30	47·02
,,	Bampton (Huntsham)	640	53·25	52·77
,,	Challacombe	850	69·68	70·28
,,	Simonsbath	1080	81·14	79·34
,,	Hawkridge (Liscombe)	980	71·77	71·59
1911	Simonsbath	1080	66·29	66·21
,,	Morchard Bishop (Hartnolls) ...	420	30·06	31·01
,,	Brushford Rectory	450	38·62	39·12
,,	Winsford School	685	50·33	50·83

It seems unnecessary to publish the daily values for all the stations dealt with, as this would occupy 100 large octavo pages; but Table XXII. gives the yearly general rainfall expressed in inches over each of the two areas dealt with, the greater area including the less. In order to convert inches of rainfall into volume the following constants may be used. For the Exe valley above Brampford Speke 1 inch of rain over the area is equal to 3497 million gallons, 561,052,800 cubic feet, or, if weight is desired, 15,610,560 tons. For the whole valley of the Exe above Exeter 1 inch of rain is equal to 6674 million gallons, 1,070,762,880 cubic feet, or 29,792,576 tons.

Annual Rainfall.

The rainfall of the years specially dealt with for the purpose of this enquiry may be compared with the average values set out in my Report on the average Annual Rainfall of the Exe Valley.

Out of the five years following those dealt with in the first Report two proved exceedingly wet. The first was 1910 with an excess of 30 per cent. in the Exe valley above Brampford Speke, which was greater than in any previous year except 1872 (+ 37), 1882 (+ 35), and 1903 (+ 30); and for the whole Exe valley an excess of 29 per cent., which was only exceeded twice, in 1872 (+ 39), and 1882 (+ 32). The second occasion was 1912, which was even wetter for the Exe valley above Brampford Speke, where the excess was 31 per cent., although for the Exe valley as a whole the excess was only 27 per cent. It may be pointed out, however, that the excessive rainfall of 1912 was very largely due to the extremely wet summer months which lay beyond the scope of the River's Research.

The average of the six years now dealt with in detail showed an excess of 5 per cent. above the 40 years' average for the Exe Valley above Brampford Speke, and 3 per cent. for the whole Exe valley above Exeter. This excess was due entirely to the two very wet years just referred to, the other four years having shown rainfall below the average, and 1908, with a deficiency of 20 per cent. for the whole Exe valley, was only exceeded in dryness on three occasions and equalled once, the years in question being 1870 (−30), 1887 (−29), 1896 (−20), and 1905 (−22). The sequence of one wet year followed by two dry years, which held good from 1888 to 1905 appears to have broken down completely, there having been six consecutive dry years before the very wet year 1910. The tendency for the average rainfall, which had apparently been diminishing for many years, to return to or exeeed the normal value is curiously enough confirmed in spite of the long run of relatively dry years; thus, extending the means of consecutive groups of five years, we have now the nine groups showing the relation to the average taken as 100, as follows, starting from 1868 :—

102, 112, 110, 95, 93, 98, 92, 98, 105.

TABLE XXII.

RAINFALL 1907–1912 COMPARED WITH THE AVERAGE 1868–1907.

	Exe above Brampford Speke.		Exe above Exeter.	
	Inches.	Per cent. of average.	Inches.	Per cent. of average.
Average 1868–1907	**47·0**	**100**	**41·8**	**100**
1907	43·5	93	38·6	92
1908	39·4	84	33·6	80
1909	45·6	97	39·5	95
1910	60·9	130	53·9	129
1911	44·7	95	39·2	94
1912	61·4	131	52·9	127
Mean 1907–12	49·3	105	43·0	103

The accompanying map (Plate 9) showing the average distribution of rainfall during the five years 1907–1911 was constructed from the annual rainfall maps for those years by the following process.

The annual rainfall maps drawn upon the scale of approximately 8 miles to 1 inch were ruled with a network of fine lines into ¼-inch squares, each representing an area of roughly 4 square miles. The points of intersection of the lines which formed these squares were so arranged as to coincide precisely on all five maps. Each point of intersection was appropriately numbered for the purpose of identification.

The rainfall at each point of intersection was read off from each map in accordance with the isohyetal lines upon it, and these values were tabulated. The total number of values thus treated was 1810, representing 362 points on each of five maps. The five values for each point, *i.e.* the estimated rainfall at that point in each of the five years, were then meaned, and the means were plotted upon a blank map which had been ruled with a similar network. Isohyetal lines were then drawn, based upon the plotted means, and the resultant map is reproduced

herewith. It does not seem necessary to print the whole of the values, as these would fill several pages.

The isohyets for the period 1907 to 1911 agree closely with those for the 40 years 1868 to 1907 (see Map V. facing p. 48), the difference being greatest in the dry area in the south, where the mean value for the 5 years was slightly below the average of a long period, whilst in the wet area over Exmoor the mean agreed closely with the long-period average.

The areas between successive isohyets on the map were measured, and the general rainfall was computed by the method described earlier in this Report. The results are as follows :—

TABLE XXIII.—GENERAL RAINFALL OF THE EXE VALLEY, 1907-1911.

ABOVE BRAMPFORD SPEKE.

	Area.	General rainfall.	Volume of rainfall.
	Sq. miles.	Inches.	Sq. miles × inches.
Less than 35 inches	23·0	33·0	759·00
35 to 40 ,, ...	49·9	37·7	1,881·23
40 ,, 45 ,, ...	49·9	42·5	2,120·75
45 ,, 50 ,, ...	38·1	47·5	1,809·75
50 ,, 55 ,, ...	25·8	52·7	1,359·66
55 ,, 60 ,, ...	24·6	57·5	1,414·50
60 ,, 65 ,, ...	22·4	63·0	1,411·20
Greater than 65 ,, ...	7·8	66·0	514·80
Total	241·5	—	11,270·89

ABOVE EXETER.

	Area.	General rainfall.	Volume of rainfall.
Less than 30 inches	5·6	29·7	166·32
30 to 35 ,, ...	133·2	33·1	4,404·06
35 ,, 40 ,, ...	153·5	36·8	5,644·96
40 ,, 45 ,, ...	49·9	42·5	2,120·75
45 ,, 50 ,, ...	38·1	47·5	1,809·75
50 ,, 55 ,, ...	25·8	52·7	1,359·66
55 ,, 60 ,, ...	24·6	57·5	1,414·50
60 ,, 65 ,, ...	22·4	63·0	1,411·20
Greater than 65 ,, ...	7·8	66·0	514·80
Total	460·9	—	18,846·00

The mean general rainfall for the five years of the Exe valley above Brampford Speke was 46·7 inches, and that of the Exe valley above Exeter 40·9 inches, these results being closely accordant with those obtained by meaning the general rainfall values worked out for the five years separately.

MONTHLY RAINFALL.

Whilst it was easy to obtain the average general rainfall of the Exe valley with which to compare the general rainfall of individual years, there is no simple method of getting at the average monthly rainfall. The greater variability of the monthly fall makes it desirable to employ records extending over a very long period, and the compilation of an immense number of monthly maps for the whole area. The comparatively small number of stations existing in earlier years makes it impossible to attempt the preparation of really trustworthy monthly averages in this way.

We have to fall back, therefore, on a method which, if not exact, serves at least to furnish a basis for comparison. This is to select the longest satisfactory records in different districts and ascertain the average proportion which each month's rainfall forms of the year's total. The stations selected for this purpose are Arlington Court, the west of Exmoor; Tiverton, a composite record; and Exeter, for each of which forty years are available. The average monthly rainfall and the percentage which each month's rainfall forms of the annual total are set out in Table XXIV.; and the similarity of the percentages at the three stations for each month appears to justify us in taking the mean of the two northern stations as representing the average monthly distribution of rain in the Exe above Brampford Speke, and the mean of the three as representing, though perhaps not quite so satisfactorily, the average monthly distribution over the whole valley. Applying these mean percentages for each month to the average general rainfall already deduced for the two areas with

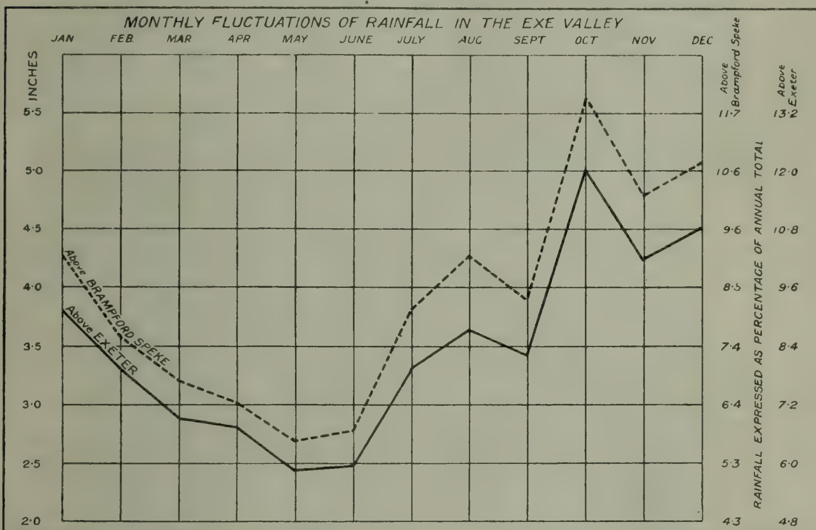


FIG. 9.

which we are dealing, we obtain Table XXV., which gives the computed general rainfall in inches for each month of the average year over the valley of the Exe above Brampford Speke, and over the whole valley of the Exe above Exeter; and these are figures which we assume as standards in comparing the rainfall of the months, during which the research was carried on, with the average. It thus appears that whether we view the smaller or larger area, we find that the driest month of the year is May, and the wettest October, the contrast being exceptionally well marked, the average rainfall for October being practically double that for May (see curves, Fig. 9). These months characterize the seasons, the three months April, May and June having together about 18 per cent. of the annual total, while the three months October, November and December have together 33 per cent. Half the annual rainfall normally occurs in the five months September to January, the other half in the seven months February to August.*

* Since this Report was written, Mr. Salter and I communicated a paper to the Royal Meteorological Society (*Quart. J. R. Met. Soc.*, vol. **41**, January, 1915, pp. 1–44)

TABLE XXIV.

AVERAGE MONTHLY RAINFALL.

	Exeter.	Tiverton.	Arlington.	As per cent. of annual total. A Exeter.	B Tiverton.	C Arlington.	Exe valley above Brampford Speke $= \frac{B + C.}{2}$	Exe valley above Exeter $= \frac{A + B + C.}{3}$
	in.	in.	in.	in.	in.	in.	in.	in.
January ...	2·82	3·44	4·92	9·0	9·1	9·1	9·1	9·1
February ...	2·64	2·93	3·95	8·5	7·8	7·3	7·6	7·9
March ...	2·22	2·64	3·64	7·1	7·0	6·7	6·8	6·9
April	2·33	2·61	3·11	7·5	6·9	5·8	6·4	6·7
May	1·84	2·30	2·87	5·9	6·1	5·3	5·7	5·8
June	1·85	2·24	3·21	5·9	6·0	5·9	5·9	5·9
July	2·30	3·01	4·45	7·4	8·0	8·2	8·1	7·9
August ...	2·50	3·30	5·11	8·0	8·7	9·5	9·1	8·7
September ...	2·50	3·11	4·53	8·0	8·2	8·4	8·3	8·2
October ...	3·77	4·46	6·62	12·1	11·7	12·3	12·0	12·0
November ...	3·11	3·78	5·53	10·0	10·0	10·3	10·2	10·1
December ...	3·29	3·95	6·06	10·6	10·5	11·2	10·8	10·8
Year	31·17	37·77	54·00	100·0	100·0	100·0	100·0	100·0

TABLE XXV.

GENERAL AVERAGE MONTHLY RAINFALL, EXE VALLEY.

	Above Brampford Speke.	Above Exeter.
	inches.	inches.
January	4·28	3·80
February	3·57	3·30
March	3·20	2·88
April...	3·01	2·80
May	2·68	2·43
June	2·77	2·47
July	3·81	3·30
August	4·28	3·64
September	3·90	3·43
October	5·64	5·01
November	4·79	4·23
December	5·07	4·51
Year	47·00	41·80

Table XXVI. sets out the percentage of the rainfall of each year under consideration which fell in each month, and, as is to be expected, the differences are very wide. Thus, the wettest month in the whole period, December, 1911, had more than a quarter of the whole rainfall of the year. In that year practically half of

on "Isomeric Rainfall Maps of the British Isles," in which calculations of the percentage which the average rainfall of each month forms of that of the year are given for the whole country, and that extended investigation fully confirms the method employed in this Report.

the rainfall was compressed into the three last months. On the other hand, the two driest months, September, 1910, and July, 1911, had less than one per cent. of the annual rainfall, and in the case of the three months, July—September, 1911, the rainfall was only one-ninth of the year's fall. No one of the years dealt with showed any close approach to the average distribution of rainfall amongst the months, the least abnormal being 1910, when, although the total quantity of rainfall in the year was the greatest with which we have to deal, the spring months were all relatively dry, and the late autumn and early winter months wet. It is probably not too much to say that, despite the general predominance of dry months in spring and of wet months in autumn and winter over the Exe valley, any month may turn out the wettest in a given year, and any month the driest, so that the variations of river-flow in the period under consideration do not necessarily correspond to those of a normal year.

TABLE XXVI.

General Rainfall of the Exe Valley above Brampford Speke.

	1907.	1908.	1909.	1910.	1911.	1912.	1907.	1908.	1909.	1910.	1911.	1912.
	ins.	ins.	ins.	ins.	ins.	ins.	Expressed as percentage of annual totals.					
January ...	2·33	3·02	2·87	7·07	2·09	6·02	5·4	7·6	6·3	11·6	4·7	9·8
February ...	2·58	3·29	0·78	7·14	3·82	3·79	5·9	8·4	1·7	11·7	8·5	6·2
March ...	1·68	4·13	5·73	1·03	2·93	8·45	3·9	10·5	12·6	1·7	6·6	13·8
April ...	5·30	3·21	3·70	3·47	3·29	—	12·2	8·1	8·1	5·7	7·4	—
May ...	3·16	2·20	2·23	3·74	1·76	—	7·3	5·6	4·9	6·1	3·9	—
June ...	3·87	0·85	2·81	3·28	3·52	—	8·9	2·2	6·2	5·4	7·9	—
July ...	2·44	3·16	3·10	4·24	0·36	—	5·6	8·0	6·8	7·0	0·8	—
August ...	3·75	5·22	2·37	6·02	2·12	—	8·6	13·2	5·2	9·9	4·7	—
September	0·89	4·03	3·38	0·37	2·66	—	2·0	10·2	7·4	0·6	5·9	—
October ...	7·56	2·93	9·17	9·08	4·68	—	17·4	7·4	20·1	14·9	10·5	—
November	3·41	2·51	2·56	7·77	5·97	—	7·8	6·4	5·6	12·7	13·4	—
December	6·51	4·87	6·88	7·71	11·48	—	15·0	12·4	15·1	12·7	25·7	—
Year ...	43·48	39·42	45·58	60·92	44·68	61·37	100·0	100·0	100·0	100·0	100·0	100·0

General Rainfall of the Exe Valley above Exeter.

	1907.	1908.	1909.	1910.	1911.	1912.	1907.	1908.	1909.	1910.	1911.	1912.
	ins.	ins.	ins.	ins.	ins.	ins.	Expressed as percentage of annual totals.					
January ...	1·92	2·17	2·34	6·01	1·60	5·36	5·0	6·4	5·9	11·2	4·1	10·1
February ...	2·07	2·70	0·64	6·04	2·80	3·53	5·4	8·0	1·6	11·2	7·1	6·7
March ...	1·27	3·82	5·57	0·88	2·63	7·42	3·3	11·4	14·1	1·6	6·7	14·0
April ...	5·14	2·88	3·14	3·12	2·73	—	13·3	8·6	8·0	5·8	7·0	—
May ...	3·01	2·02	1·76	3·45	1·54	—	7·8	6·0	4·5	6·4	3·9	—
June ...	3·13	0·74	2·79	2·87	2·97	—	8·1	2·2	7·1	5·3	7·6	—
July ...	1·98	2·38	2·80	3·55	0·35	—	5·1	7·1	7·1	6·6	0·9	—
August ...	2·83	4·24	2·18	5·40	2·07	—	7·4	12·6	5·5	10·0	5·3	—
September	0·78	3·35	2·74	0·33	2·22	—	2·0	10·0	6·9	0·6	5·7	—
October ...	7·35	2·97	7·48	7·89	4·44	—	19·0	8·8	18·9	14·6	11·3	—
November	3·23	2·00	1·86	6·79	5·14	—	8·4	6·0	4·7	12·6	13·1	—
December	5·89	4·33	6·22	7·57	10·72	—	15·2	12·9	15·7	14·1	27·3	—
Year ...	38·60	33·60	39·52	53·90	39·21	52·86	100·0	100·0	100·0	100·0	100·0	100·0

Table XXVII. contrasts all the wettest and driest months occurring between January, 1907, and March, 1912, where it will be seen that in the Exe valley above Brampford Speke seven months had a general rainfall greater than 7·50 inches, and of these very wet months three were consecutive, namely, October–December, 1910, this being the most remarkable wet period so far as monthly totals are concerned with which we have to deal. The lower part of Table XXVII. sets out all the months in which the general rainfall over the Exe valley above Exeter was less than one inch. Of these there were six examples, no two of which were consecutive, and only two showed a general rainfall less than half an inch.

TABLE XXVII.

MONTHS IN WHICH THE GENERAL RAINFALL EXCEEDED 7·00 INCHES OVER THE EXE VALLEY ABOVE EXETER, OR 7·50 INCHES OVER THE EXE VALLEY ABOVE BRAMPFORD SPEKE FROM JANUARY, 1907, TO MARCH, 1912.

Date.	Exe above Brampford Speke. Rainfall. Inches.	Exe above Exeter. Rainfall. Inches.
October, 1907	7·56	7·35
,, 1909	9·17	7·48
,, 1910	9·08	7·89
November, 1910	7·77	6·79
December, 1910	7·71	7·57
,, 1911	11·48	10·72
March, 1912	8·45	7·42

MONTHS IN WHICH THE GENERAL RAINFALL WAS LESS THAN 1·00 INCH OVER THE EXE VALLEY ABOVE EXETER, OR THE EXE VALLEY ABOVE BRAMPFORD SPEKE FROM JANUARY, 1907, TO MARCH, 1912.

Date.	Exe above Brampford Speke. Rainfall. Inches.	Exe above Exeter. Rainfall. Inches.
September, 1907	·89	·78
June, 1908	·85	·74
February, 1909	·78	·64
March, 1910	1·03	·88
September, 1910	·37	·33
July, 1911	·36	·35

While the incidence of monthly rainfall within the year to which we have been referring gives the best clue to the seasonal *régime* of river flow, it is desirable also to consider the rainfall of each month in its relation to the long-period average for that particular month. This is done in Table XXVIII. Considering each month by itself we find that in the period under consideration wet and dry months were practically equal in number. On account of the great variation the mere division into months with less and more than the average rainfall has little significance, so we have adopted five degrees of comparison: *Normal,* when the rainfall is within 25 per cent. of the average; *Wet*, when the excess is greater than 25 per cent. but less than 100 per cent.; *Very Wet*, when there was more than twice the average rainfall; *Dry*, when the deficiency though greater than 25 per cent. was less than

75 per cent.; and *Very Dry*, when less than one quarter of the average rainfall occurred. In the Exe valley above Brampford Speke 23 of the 63 months can be classed as Normal, 16 as Wet and 3 as Very Wet, 17 as Dry and 4 as Very Dry. Every month except January is represented in the Normal group, every month except July and September is represented in the Wet or Very Wet groups, and every month except April and December is represented in the Dry or Very Dry classes. February is the only month which figures in all five classes, for we may take its percentage of 200 in 1910 as being so exactly on the border-line between Wet and Very Wet as to belong to either. March, which had the greatest percentage excess of any month, in 1912, showed the largest range, the driest March having had only 32 per cent. of the average, while the wettest had 264 per cent. It is worthy of note that during the period under discussion the rainfall of April never once fell below the average, yet there was only one April which could be classed as Wet within the limits adopted above. December, on the other hand, was only once below the average, and on every other occasion was Wet or Very Wet. July and September each exceeded their average rainfall only on one occasion. The data for the whole Exe valley above Exeter give very similar results.

TABLE XXVIII.

General Rainfall of the Exe Valley as a percentage of the Average.

	Above Brampford Speke.						Above Exeter.					
	1907.	1908.	1909.	1910.	1911.	1912.	1907.	1908.	1909.	1910.	1911.	1912.
January ...	54	71	67	165	49	141	51	57	62	158	42	141
February ...	72	92	22	200	107	106	63	82	19	183	85	107
March ...	53	129	179	32	92	264	44	133	193	31	91	258
April ...	176	107	123	115	109	—	184	103	112	110	98	—
May ...	118	82	83	140	66	—	124	83	72	142	63	—
June ...	140	31	101	118	127	—	127	30	113	116	120	—
July ...	64	83	81	111	9	—	60	72	85	108	11	—
August ...	88	122	55	141	50	—	78	116	60	148	57	—
September	23	103	87	9	68	—	23	98	80	10	65	—
October ...	134	52.	162	161	83	—	147	59	149	157	89	—
November	71	52	53	163	125	—	76	47	44	160	121	—
December	128	96	136	152	226	—	131	96	138	168	238	—
Year ...	93	84	97	130	95	131	92	80	95	129	94	127

Daily Rainfall.

Tables were prepared giving the general rainfall of the Exe valley above Brampford Speke and of the whole Exe valley above Exeter for each day from January 1, 1907 to March 31, 1912, but as daily values for the stream gauges are not to be published in the Committee's Report it has been considered unnecessary to insert the tables of daily rainfall. The method by which the figures were arrived at has been explained in the introductory section of this report. In 32 cases the daily rainfall was deduced from maps constructed in the same way as the monthly and annual maps. Table XXIX. gives a comparison of the computation from the maps with the mean of 10 well-distributed stations for the Exe above Brampford Speke, and of 20 well-distributed stations for the whole Exe valley above Exeter. The instances dealt with, it must be remembered, are all exceptional, having been chosen

either on account of the excessive rainfall of the day or the exceptional geographical distribution of the rain, and it is highly improbable that as great a disparity between the two methods of calculating general rainfall would be found in other cases. Four of the daily maps are reproduced herewith as specimens representing the more interesting varieties of distribution.

TABLE XXIX.

Exe Valley Rainfall.

Date.	Above Brampford Speke.		Above Exeter.	
	By 10 stations.	By map.	By 20 stations.	By map.
	Inches.	Inches.	Inches.	Inches.
January 1, 1907	·679	·558	·500	·432
April 20, ,, ...	·690	·780	·659	·720
August 17, ,, ...	·875	·940	·767	·827
October 16, ,, ...	1·154	1·275	1·008	1·114
,, 28, ,, ...	·492	·577	·779	·798
December 4, ,, ...	1·151	1·065	1·021	1·005
January 7, 1908	·824	·864	·600	·654
July 16, ,, ...	1·323	1·336	·976	1·011
August 31, ,, ...	1·140	1·191	·836	·887
October 19, ,, ...	·362	·440	·567	·526
November 21, ,, ...	·868	·903	·628	·695
March 5, 1909	·641	·708	·762	·850
,, 8, ,, ...	·684	·707	1·010	·999
May 26, ,, ...	1·144	1·093	·840	·829
October 15, ,, ...	1·566	1·463	1·084	1·055
December 2, ,, ...	1·234	1·238	1·009	1·004
,, 21, ,, ...	1·094	1·112	1·275	1·286
January 23, 1910	1·455	1·474	1·283	1·321
May 17, ,, ...	·763	·783	·774	·871
August 28, ,, ...	·666	·697	·900	·883
October 11, ,, ...	1·228	1·379	1·047	1·189
,, 12, ,, ...	1·691	1·586	1·298	1·202
,, 31, ,, ...	1·393	1·348	1·021	·999
December 8, ,, ...	1·084	1·109	1·133	1·171
June 19, 1911	·600	·620	·526	·575
,, 29, ,, ...	·683	·678	·521	·516
August 5, ,, ...	·429	·460	·582	·665
December 8, ,, ...	1·016	·998	·932	·905
,, 14, ,, ...	·846	·858	·890	·925
January 4, 1912	·665	·581	·472	·426
,, 6, ,, ...	·924	·920	·799	·808
March 4, ,, ...	1·304	1·310	1·222	1·233

The first of these, Fig. 10, represents October 28, 1907, a day on which the heaviest rainfall occurred in the south-west of the district, more than one inch of rain falling to the south of a line passing through Brampford Speke and practically enclosing the Creedy valley, while less than half an inch of rain fell to the north of Dulverton, Exmoor having the lowest rainfall in the whole valley, the distribution being thus very nearly an inversion of the normal. On this occasion the general rainfall as deduced from the map was ·798 inch; that from the 20 stations being ·779 inch, the slight difference between the two methods being easily explained by the fact that the stations selected to give a fair representation of the normal distribution of rain were equally appropriate when the distribution was exactly reversed.

The second map, Fig. 11, July 16, 1908, represents what we must regard as an exaggeration of the normal distribution of rain, that is to say, the distribution of rain on this wet day was similar to the distribution in an average month or year, the only difference being that the wettest area on Exmoor showed a proportionally heavier rainfall than the minor centres of relatively high rainfall in the south-west and east. More than one inch of rain fell over the whole of Exmoor north of Dulverton, and more than two inches on the summit of the moor. The rainfall diminished to half an inch at Exeter, and increased again on the slopes of Dart-

FIG. 10.

moor and in the south of the Culm valley. The general rainfall deduced from the map was 1·011 inch, and the mean of the 20 stations was ·976 inch. The difference between the two methods here is not great, though a trifle more than in the previous case.

The third map, Fig. 12, for October 19, 1908, shows an altogether abnormal distribution, more than two inches occurring at a point near the head of the Culm valley, and more than one inch falling over the upper half of that valley, the rainfall diminishing rapidly to the westward, falling off to a quarter of an inch along a line running from Exeter through Brampford Speke and Tiverton, and becoming

less than one-tenth of an inch in the extreme west of the Creedy and upper Exe valleys. The general rainfall computed from the map is ·526 inch, and that from the 20 stations ·567 inch, the proportional discrepancy being twice as great as in the case of the normally distributed rainfall on July 16, 1908.

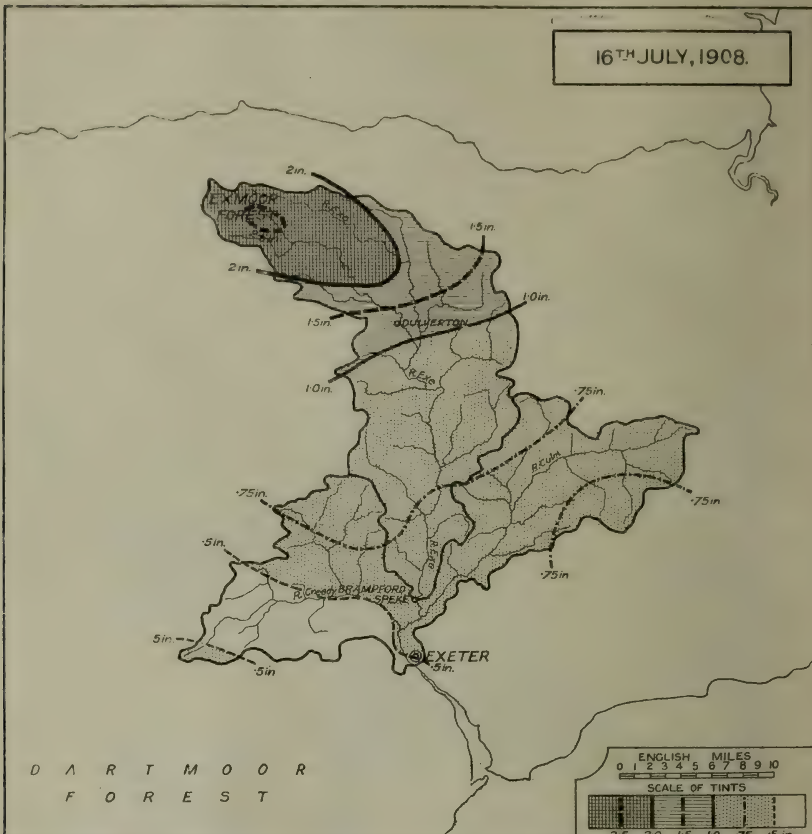


FIG. 11.

The fourth map, Fig. 13, that of May 17, 1910, is also of a very exceptional character. More than an inch fell over a large area in the very centre of the valley including parts of the Culm, Exe and Creedy, and the rainfall diminished all round, the heads of all the valleys having the lowest fall, least of all, only half an inch occurring on the summit of Exmoor. The general rainfall computed from the map was ·871 inch, that from the 20 stations was ·774 inch, a very considerable difference, accounted for by the larger number of stations falling in the dry area.

Table XXX. gives an analysis of the daily general rainfall of the Exe valley above Brampford Speke and of the whole valley of the Exe above Exeter. It shows that, of the 1917 consecutive days considered, 431 were rainless. The number with less than ·10 inch was 868, between ·10 inch and ·50 inch 517, while there were only 101 with more than half an inch. Eleven days had a general

rainfall exceeding one inch, and none had so much as an inch and a half. It is somewhat remarkable in so long a period that there were so few instances of very high daily rainfall, and, indeed, during the whole time there was no localized heavy rain of the thunderstorm type such as occurred frequently during the same period in the south-east of England; and, of course, there was nothing approaching even in a remote degree the unprecedented rainfall which occurred in East Anglia on August 26, 1912, on which occasion a general rainfall exceeding 6 inches fell over an area much greater than that of the whole Exe valley.

FIG. 12.

It is evident that we have to deal rather with numerous falls of moderate intensity than with alternating periods of intense drought and torrential rainfall; and an examination of the detailed tables, which are not inserted, shows the comparatively greater frequency of a run of consecutive wet days than a run of consecutive dry days. Table XXXI. sets out all the long runs of days with and without rain in the Exe valley above Brampford Speke. It shows that there were twenty-one occasions when rain fell at one or more of the ten stations studied for this valley on every one of twenty consecutive days, and the longest of these periods with daily rain was for seventy-two days from December 21, 1909 to March 2, 1910,

with a total general rainfall of 16·426 inches and this, it must be observed, at a time of year when there was practically no evaporation from the ground. A still larger amount of rain, 16·664 inches fell in the fifty-seven days with rain from October 31 to December 26, 1910. It is obvious that in such periods the rivers are supplied with rain more steadily and uniformly than at any others. The opposite condition occurs when many days elapse without rain falling, and Table XXXI. shows that there were very few occasions when more than ten consecutive rainless

Fig. 13.

days occurred, and only thirty-two when five or more days passed without rain. It is perhaps necessary to caution the reader against comparing these periods of days with and without rain for an area such as a river valley with the droughts and rain spells recorded for individual stations, the limit of rain in the former case has been taken as a general fall of ·001 inch which would be produced by a recorded fall of ·01 inch at one of the ten selected stations, even though no rainfall was recorded at the nine others. The unit of a rain day for a single station is always taken at ·01 inch, no regard being paid to smaller falls.

Table XXXII. gives similar data for the whole Exe valley above Exeter,

TABLE XXX.

Daily General Rainfall of the Exe Valley, January, 1907—March, 1912.

	·000.	·001—·009.	·010—·099.	·100—·199.	·200—·299.	·300—·399.	·400—·499.	·500—·599.	·600—·699.	·700—·799.	·800—·899.	·900—·999.	1·000—1·099.	1·100—1·199.	1·200—1·299.	1·300—1·399.	1·400—1·499.	1·500—1·599.	1·600—1·699.	1·700—1·799.	1·800—1·899.	1·900—1·999.	More than 2·000.	Total.
Above Brampford Speke.																								
1907	75	45	116	52	32	19	9	8	2	3	1	1	1	—	1	—	—	—	—	—	—	—	—	365
1908	93	70	87	47	29	16	10	6	—	2	2	2	—	1	—	1	—	—	—	—	—	—	—	366
1909	101	48	98	45	20	17	14	8	5	3	—	1	2	1	1	—	1	—	—	—	—	—	—	365
1910	73	42	104	47	23	23	20	7	7	11	1	1	1	1	—	2	1	1	—	—	—	—	—	365
1911	115	50	83	30	30	15	19	7	10	2	3	1	—	—	—	—	—	—	—	—	—	—	—	365
1912	9	9	24	16	7	11	5	6	—	1	1	1	—	—	—	1	—	—	—	—	—	—	—	91
Total ...	466	264	512	237	141	101	77	42	24	22	8	7	4	3	2	4	2	1	—	—	—	—	—	1917
Per cent....	24·3	13·8	26·7	12·3	7·3	5 3	4·0	2·2	1·3	1·1	0·4	0·4	0·2	0·2	0·1	0·2	0·1	0·1	—	—	—	—	—	100·0
Above Exeter.																								
1907	69	61	121	51	28	9	13	5	1	4	1	—	1	1	—	—	—	—	—	—	—	—	—	365
1908	86	80	96	41	32	14	5	4	4	2	1	—	1	—	—	—	—	—	—	—	—	—	—	366
1909	93	64	104	34	28	15	8	10	1	1	2	2	2	—	1	—	—	—	—	—	—	—	—	365
1910	68	51	107	50	27	20	8	16	7	—	5	2	—	2	1	1	—	—	—	—	—	—	—	395
1911	106	64	85	30	32	16	15	8	5	2	—	2	—	—	—	—	—	—	—	—	—	—	—	365
1912	9	9	26	13	14	7	7	1	3	—	1	—	—	—	1	—	—	—	—	—	—	—	—	91
Total ...	431	329	539	219	161	81	56	44	21	9	10	6	4	3	3	1	—	—	—	—	—	—	—	1917
Per cent....	22·5	17·2	28·0	11·4	8·4	4·2	2·9	2·3	1·1	0·5	0·5	0·3	0·2	0·2	0·2	0·1	—	—	—	—	—	—	—	100·0

TABLE XXXI.

General Rainfall of the Exe Valley above Brampford Speke, January, 1907—March, 1912.

Periods of 20 or more days, with rain every day.					Periods of 5 or more days without measurable rain.		
Began	Ended	No. of days.	Total rain.	Rain per day.	Began	Ended	No. of days.
			Inches.	Inches.			
Apr. 20, 1907	May 12, 1907	23	4·402	·191	Mar. 23, 1907	Mar. 31, 1907	9
June 9, ,,	July 10, ,,	32	4·772	·149	July 15, ,,	July 19, ,,	5
Sept. 29, ,,	Oct. 30, ,,	32	7·606	·238	Sept. 8, ,,	Sept. 19, ,,	12
Nov. 22, ,,	Dec. 25, ,,	34	8·383	·247	Apr. 5, 1908	Apr. 9, 1908	5
Feb. 13, 1908	Mar. 10, 1908	27	4·643	·172	June 19, ,,	July 6, ,,	18
Sept. 7, ,,	Sept. 28, ,,	22	3·018	·137	July 19, ,,	,, 23, ,,	5
Dec. 2, ,,	Dec. 23, ,,	22	3·337	·152	Aug. 4, ,,	Aug. 8, ,,	5
Mar. 2, 1909	Mar. 25, 1909	24	4·634	·193	Nov. 2, ,,	Nov. 9, ,,	8
July 13, ,,	Aug. 2, ,,	21	2·206	·105	Jan. 21, 1909	Jan. 28, 1909	8
Sept. 27, ,,	Oct. 29, ,,	33	10·311	·312	Apr. 3, ,,	Apr. 10, ,,	8
Nov. 23, ,,	Dec. 13, ,,	21	5·620	·268	May 2, ,,	May 13, ,,	12
Dec. 21, ,,	Mar. 2, 1910	72	16·426	·228	,, 19, ,,	,, 23, ,,	5
July 14, 1910	Aug. 9, ,,	27	4·644	·172	Aug. 3, ,,	Aug. 14, ,,	12
Aug. 11, ,,	Sept. 2, ,,	23	4·440	·193	Sept. 14, ,,	Sept. 22, ,,	9
Oct. 10, ,,	Oct. 29, ,,	20	6·986	·349	Nov. 17, ,,	Nov. 22, ,,	6
,, 31, ,,	Dec. 26, ,,	57	16·664	·292	Mar. 19, 1910	Apr. 1, 1910	14
Feb. 12, 1911	Mar. 23, 1911	40	6·584	·165	June 13, ,,	June 19, ,,	7
Oct. 16, ,,	Nov. 20, ,,	36	9·736	·270	July 8, ,,	July 13, ,,	6
Nov. 26, ,,	Dec. 31, ,,	36	11·923	·331	Sept. 3, ,,	Sept. 9, ,,	7
Jan. 3, 1912	Jan. 25, 1912	23	6·020	·262	,, 17, ,,	,, 24, ,,	8
*Feb. 2, ,,	Mar. 31, ,,	59	12·240	·207	Oct. 4, ,,	Oct. 9, ,,	6
					Jan. 29, 1911	Feb. 2, 1911	5
					Apr. 9, ,,	Apr. 16, ,,	8
					May 15, ,,	May 22, ,,	8
					June 3, ,,	June 14, ,,	12
					July 2, ,,	July 16, ,,	15
					,, 18, ,,	,, 25, ,,	8
					Aug. 14, ,,	Aug. 19, ,,	6
					Sept. 5, ,,	Sept. 9, ,,	5
					,, 14, ,,	,, 18, ,,	5
					Oct. 8, ,,	Oct. 12, ,,	5
					Jan. 26, 1912	Feb. 1, 1912	7

including the above. Whilst most of the periods of consecutive days with rain were identical in duration with those in the Exe Valley above Brampford Speke considered by itself, they were on the whole slightly longer and more numerous. There were twenty-two periods of twenty or more days with rain, the longest being from December 21, 1909 to March 2, 1910, seventy-two days, during which the general rainfall was 14·134 inches. In the period of fifty-seven days from October 31 to December 26, 1910, mentioned above, the general rainfall over the whole Exe valley above Exeter was 15·254 inches. There were twenty-eight periods of five or more days without measurable rain in general, and only six of these extended to ten days or more, the longest being seventeen days from June 20 to July 6, 1908. Since the number of stations used in computing the general rainfall was twenty, and the minimum amount of general rainfall considered was ·001 inch, a day on which a fall of only ·01 inch occurred at one station only of the twenty would be con-

* Possibly longer.

TABLE XXXII.

General Rainfall of the Exe Valley above Exeter, January, 1907—March, 1912.

Periods of 20 or more days, with rain every day.					Periods of 5 or more days, with measurable rain.		
Began	Ended	No. of days.	Total rain.	Rain per day.	Began	Ended	No. of days.
			Inches.	Inches.			
Apr. 20, 1907	Mar. 14, 1907	25	4·105	·164	Mar. 23, 1907	Mar. 31, 1907	9
June 9, ,,	July 11, ,,	33	3·805	·115	July 15, ,,	July 19, ,,	5
Sept. 26, ,,	Nov. 9, ,,	45	8·178	·182	Sept. 8, ,,	Sept. 19, ,,	12
Nov. 22, ,,	Dec. 25, ,,	34	7·380	·217	June 20, 1908	July 6, 1908	17
Feb. 13, 1908	Mar. 10, 1908	27	3·934	·146	July 18, ,,	July 23, ,,	6
Apr. 18, ,,	May 18, ,,	31	3·840	·124	Aug. 4, ,,	Aug. 8, ,,	5
Sept. 7, ,,	Sept. 28, ,,	22	2·604	·118	Nov. 3, ,,	Nov. 9, ,,	7
Dec. 2, ,,	Dec. 23, ,,	22	2·929	·133	Jan. 21, 1909	Jan. 26, 1909	6
Mar. 1, 1909	Mar. 31, 1909	31	5·570	·180	Apr. 3, ,,	Apr. 10, ,,	8
July 13, ,,	Aug. 2, ,,	21	1·925	·092	May 2, ,,	May 13, ,,	12
Sept. 27, ,,	Nov. 6, ,,	41	8·578	·209	May 19, ,,	May 23, ,,	5
Nov. 23, ,,	Dec. 13, ,,	21	4·644	·221	Aug. 3, ,,	Aug. 14, ,,	12
Dec. 21, ,,	Mar. 2, 1910	72	14·134	·196	Sept. 14, ,,	Sept. 20, ,,	7
July 19, 1910	Aug. 9, ,,	22	3·264	·148	Nov. 18, ,,	Nov. 22, ,,	5
Aug. 11, ,,	Sept. 2, ,,	23	3·964	·172	Mar. 22, 1910	Apr. 1, 1910	11
Oct. 10, ,,	Oct. 29, ,,	20	6·285	·314	June 13, ,,	June 17, ,,	5
Oct. 31, ,,	Dec. 26, ,,	57	15·254	·268	July 8, ,,	July 13, ,,	6
Feb. 10, 1911	Mar. 23, 1911	42	5·328	·127	Sept. 3, ,,	Sept. 9, ,,	7
Oct. 12, ,,	Nov. 20, ,,	40	8·823	·221	Sept. 17, ,,	Sept. 24, ,,	8
Nov. 26, ,,	Dec. 31, ,,	36	11·092	·308	Jan. 29, 1911	Feb. 2, 1911	5
Jan. 3, 1912	Jan. 25, 1912	23	5·360	·233	Apr. 9, ,,	Apr. 16, ,,	8
*Feb. 2, ,,	Mar. 31, ,,	59	10·950	·186	June 3, ,,	June 8, ,,	6
					June 10, ,,	June 14, ,,	5
					July 2, ,,	July 16, ,,	15
					July 18, ,,	July 25, ,,	8
					Aug. 14, ,,	Aug. 19, ,,	6
					Sept. 14, ,,	Sept. 18, ,,	5
					Jan. 26, 1912	Feb. 1, 1912	7

sidered a rainless day, though if two stations of the twenty recorded ·01 inch, the day would rank as a day with rain.

This Report has been concerned rather with the preparation of data for discussion along with the stream-flow observations than with the object of presenting a complete study of the rainfall conditions. The Report includes, however, all the data necessary for the study of the areas concerned throughout the period, and I wish to lay stress upon the fact that general conclusions may be drawn with far greater confidence from the general rainfall of an area than from the records of an individual station, and this is especially true with regard to any attempt to deduce periodic relationships from observed data.

I have been assisted in the compilation of this Report by Mr. Carle Salter, Assistant Director of the British Rainfall Organization. The statistics have been compiled mainly by Mr. H. E. Carter, chief computer, while the maps have been drawn by Mr. D. S. Salter, cartographer to the British Rainfall Organization.

* Possibly longer.

ON THE AREA OF EACH BASIN AND THE ELEVATION OF DIFFERENT PARTS OF IT.

The only map showing the water-partings of the rivers of England and Wales appears to be "Rivers and their Catchment Basins," on a scale of 10 miles to the inch, published by the Ordnance Survey under the superintendence of Colonel Sir Henry James. Not only was the scale too small for our purpose, but the adoption of the map was prohibited by the fact that the measurements of the basin included the areas which drain into tidal waters. It became necessary, therefore, to draw in the water-parting of that area only which was drained by the river above our lowest gauge, and it seemed advisable also to determine the rest of the parting on a map of larger scale and more modern topography.

Much of the parting could be fixed with sufficient accuracy by help of the data given on the 6-inch Ordnance maps, but there were many pathless tracts where considerable error would have been involved without examination of the ground ; even so the precise determination of the line proved to be far from easy. Not infrequently the parting ran upon narrow strips of plateau-form, devoid of features, and its exact position on the level surface was difficult to recognize. Nor was it possible to say what proportion of the water which soaked into the ground went to feed the springs on the one side or the other. Elsewhere there were broad tracts of low relief, more or less artificially drained, where it was impossible to trace a precise boundary between the basins. But though for these reasons the lines drawn lack precision in detail, there is no reason to suspect an accumulating error in either direction, and the estimates of area founded upon them are probably a close approximation to the truth.

THE EXE BASIN.

The tracing of the water-parting of the Exe basin above Exeter quay, and of various subsidiary partings, was carried out by Mr. E. F. Elton and Mr. H. O. Beckitt. In all cases where the data given on the 6-inch Ordnance maps proved to be insufficient, the positions of the divides were determined by inspection of the ground.

The boundaries of the geological formations were transferred to the maps in use from the Old Series 1-inch Geological maps, except as regards the area included in the New Series Sheet 325 (Exeter), there being no more recent survey available for the remainder of the basin.

Mr. Elton reports as follows :—

Measurements of Areas in the Exe Basin.

By E. F. ELTON.

The areas given in the following table of the upper Exe, the Culm, and the Creedy are those of such parts of their basins as drain into them above the gauges at Brampford Speke, Silverton, and Pynes bridge respectively. The intergauge area is that which drains into these streams between the gauges mentioned and the gauge on the Exeter quay. The sum of the four areas is the area of the Exe basin above tidal waters.

Some account of the steps taken to obtain the above figures may be desirable, to give an idea of the degree of accuracy that may be expected from them.

The Exe basin occupies the whole or part of 113 sheets of the 6-inch map, and

the boundary of the several areas required was marked on these sheets. As a rule the information given on these maps left little room for doubt as to the position of the boundary; but where it seemed uncertain, with the assistance of Mr. H. O. Beckitt, I determined its position on the spot. For this purpose we put upwards of 70 miles of boundary on to the 6-inch sheets in the field. The sheets were then coloured to show the geology of the basin.

To measure these areas a Stanley and Amsler's patent compensating planimeter was provided. This instrument has the advantage over the ordinary planimeter that it can be adjusted so as to compensate for the shrinking or stretching of the map, which saves the calculation otherwise necessary for each sheet measured. As sold, the planimeter is arranged to measure maps of different scales; but I found it convenient to have it further engraved so as to read areas from the 6-inch map in the largest possible unit, *i.e.* in units of 300 acres. As the area of a sheet is known, it was possible both to check the work and to estimate the accuracy of the planimeter as each sheet was completed, and it was evident that the compensation for shrinkage and stretching was remarkably successful.

TABLE XXXIII.

EXE BASIN ABOVE TIDAL WATERS.

Basin of	Devonian.	Culm measures.	New Red Sandstone.	Limestone.	Upper Greensand.	New Red Marl.	Igneous.	Alluvial.	Total in acres.
	Acres.	Acres.	Acres.	Acres.	Acres.	Acres.	Acres.	Acres.	Acres.
Upper Exe	82,684·68	50,600·58	16,826·82	311·19	—	—	461·01	2732·64	153,616·92
Creedy ...	—	44,986·29	19,119·78	—	—	—	652·95	1811·76	66,570·78
Culm ...	—	2,917·86	34,852·23	419·46	17,375·40	6171·24	95·70	3691·23	65,523·12
Intergauge	—	3,879·60	3,496·80	—	—	—	346·47	1927·05	9,649·92
	82,684·68	102,384·33	74,295·63	730·65	17,375·40	6171·24	1556·13	10,162·68	295,360·74

Total area of basin, 295,360·74 acres = 461·50[115625] square miles.

These errors in the length and breadth of each sheet have to be known in percentages of the proper dimensions, and I therefore had a rule made showing on one edge a length of 12 inches, and on the other edge a length of 18 inches, each divided into tenths and hundredths of the entire length, so that the percentage of error could be read directly. In ordering a rule of this sort it is important to remember that it must be longer than 18 inches, say 19·8 inches, since maps stretch as well as shrink.

The first actual measurement made is of the length and breadth of the sheet. The errors are combined and the necessary adjustment made in the planimeter. I then measured each area into which the sheet was divided from three up to seven times, or even oftener, according to its difficulty, and took the mean of the measurements. When this had been done for all sections of a sheet, the sum of the measurements obtained ought, of course, to have been 6 square miles. There was generally some small error, which I distributed over the sections of the sheet in proportion to their area.

The measurements of the areas lying above and below certain contour-lines were undertaken by Mr. G. E. L. Carter. When, however, all of Sheets 294, 311, 324, and 310 had been completed, illness interrupted the work, and the whole was checked and finished by Mr. H. O. Beckitt.

Measurements of Inter-Contour Areas in the Exe Basin.

By G. E. L. CARTER and H. O. BECKIT.

TABLE XXXIV.

Sheet of the one-inch map.	Above 1500 ft.	1250 to 1500 ft.	1000 to 1250 ft.	800 to 1000 ft.	600 to 800 ft.	400 to 600 ft.	200 to 400 ft.	Below 200 ft.	Total.
	Acres.	Acres.	Acres.	Acres.	Acres.	Acres.	Acres.	Acres.	
293 Barnstaple	995	6,717	2,378	54	—	—	—	—	10,144
294 Dulverton...	226	6,065	26,922	20,322	11,162	6,047	339	—	71,083
309 Chulmleigh	—	—	—	—	10	54	—	—	64
310 Tiverton ...	—	—	—	5,482	28,859	31,518	35,037	3,403	104,299
311 Wellington	—	—	—	7,089	11,208	10,175	3,650	—	32,122
324 Okehampton	—	—	—	258	4,750	7,448	4,454	—	16,910
325 Exeter ...	—	—	—	49	1,674	11,527	24,320	21,132	58,702
Total	1221 = ·4% of total	12,782 = 4·4% of total	29,300 = 9·9% of total	33,254 = 11·3% of total	57,663 = 19·7% of total	66,769 = 22·8% of total	67,800 = 23·1% of total	24,535 = 8·4% of total	293,324 acres, or 458·32 sq. miles

14·7% of basin over 1000 ft.

65·6% of basin between 200 and 800 ft.

54·3% of basin below 600 ft.

From this table the following percentages may be deduced :—

The Devonian, Culm measures, New Red Marl, and Igneous rocks may be regarded as impervious formations, and occupy 192,796 acres.

The New Red Sandstone, Limestone, Upper Greensand, and Alluvial Deposits may be regarded as pervious, and occupy 102,565 acres.

Limestone occupies 731 acres, but Upper Greensand and New Red Marl, which are both apt to contain a good deal of carbonate of lime, occupy together 23,546 acres.

	Acres.	Percentage of area of basin.
Impervious	192,796	65·3
Pervious	102,565	34·7
Limestone	731	0·25
Calcareous strata	23,546	7·97
Non-calcareous strata ...	271,084	91·78

THE MEDWAY.

The tracing of the water-parting of the Medway above Allington lock was undertaken by Mr. E. W. Dann, who reports that "the water-parting was determined as far as possible on the ground itself, whither the 6-inch quarter-sheet was taken. The line had been roughly indicated on the 1-inch sheets first, and from them each day's work was plotted out. It was found that small variations from the conjectural divide were frequent; indeed, it is doubtful whether very much could be really accurately mapped, even if 25-feet contours were interpolated. These slight variations, however, could have very little effect upon the table of measurements below." With reference to the nature of the field work involved, Mr. Dann writes that "the orographical features south of the Redhill-Bletchingley Greensand ridge are

so indeterminate that the distinguishing of the Mole *régime* from that of the Medway requires very close attention to every fold of the ground. Near Smallfield Place (due east of Horley) a ridge of less than 15 feet in height marks the divide."

The boundaries of the geological formations mentioned in the table were enlarged from the Old Series 1-inch maps, there being no more recent survey available.

In making the measurements of areas enumerated in the tables which follow, the general plan followed by Mr. Elton in the case of the Exe was at first adopted by Mr. Dann. He concluded, however, that the errors due to shrinkage and expansion of the paper were so small that the fine adjustment on the planimeter was not required for use on more than half the sheets of the map. It seemed clear that the general results arrived at would not be materially affected by such slight variations as were revealed by the special engine-divided scale used.

The Medway Basin above Allington Lock.

By E. W. DANN.

Measurements upon Six-inch Quarter-sheets.

	Acres.	
Alluvium	26,948·7	pervious, non-calcareous.
Eocene	221·9	impervious, non-calcareous.
Chalk	4,878·3	pervious, calcareous.
Upper Greensand and Gault	6,485·8	impervious, calcareous.
Lower Greensand	47,760·0	pervious, calcareous.
Weald clay	116,346·7	impervious, non-calcareous.
Tunbridge Wells sand and Grinstead clay ...	72,631·2	pervious, non-calcareous.
Wadhurst clay	39,791·2	impervious, non-calcareous.
Ashdown sand	35,996·1	pervious, non-calcareous.
Total area of Medway basin	351,059·9	= 548·53 square miles.

Measurements upon One-inch Maps.

The inter-contour spaces enumerated below were measured upon the 1-inch maps in square centimetres :—

Elevation in feet.	Area on map in square centimetres.	Percentage of total.
Over 600	46·6	1·4
400–600	217·8	5·9
200–400	1775·8	48·5
Under 200	1620·7	44·2
	3660·9	100·0

It will be seen that the pervious formations occupy an area of 188,214·3 acres as compared with an area of 162,845·6 acres occupied by impervious strata. Calcareous formations, including Upper Greensand Gault and Lower Greensand, which can only be described as being in part calcareous, occupy 59,124·1 acres, as against 291,935·8 acres occupied by non-calcareous strata. These figures yield the following approximate percentages :—

Pervious formations occupy 53·6 per cent. of the basin.
Impervious ,, ,, 46·4 ,, ,, ,,
Calcareous ,, ,, 17·0 ,, ,, ,,
Non-calcareous ,, ,, 83·0 ,, ,, ,,

The Severn Basin.

The tracing of the boundary of the Severn basin, and the measurement of the area of the basin above Worcester, were undertaken by Dr. J. S. Owens. The locating of the water-parting presented unusual difficulties in the northern and north-eastern parts of the basin. The boundary between the drainages of the Severn and those of the Dee, Weaver, and Trent crosses ground of small altitude and low relief in Shropshire and Staffordshire, and in the Black Country is largely artificial. The difficult work of tracing it across the indefinite ground was carried out by Mr. L. A. Sellick under Dr. Owens's superintendence. The greater part of the water-parting, however, was drawn upon the Ordnance maps on the scale of ½ inch = 1 mile by reference to the levels marked upon them. The following extracts from a report by Mr. Sellick shows that in certain areas a map may be misleading without inspection of the ground.

Mr. Sellick's Report.

The following sections of water-parting were visited and the line marked on the 1-inch maps on the spot:—

1. In the neighbourhood of Market Drayton, between Ightfield and Betton Moss.
2. Bishop's Wood, between Bishop's Offley and Fair Oak.
3. Ellesmere and St. Martin's, between Bettisfield and Selattyn.
4. Church Stretton, between Pole Bank and Hope Bowdler Hill.
5. Fallerdig, near Carno, between Bryn Gwyn and Moel Gloria.
6. Wolverhampton, between Blakenhall and Perton.

In the valley between Moreton Say and Longford there is a level stretch of country which has been artificially drained. The land north of the road connecting these villages is drained to the River Duckow, that lying south to the Bailey brook. The main drain, which, when visited, was dry, appears on the map to pass under the road, but local inquiry proved this supposition to be false, the road itself forming the water-parting at this point. A similar situation is evident near Little Cloverley. The lake on the grounds of Cloverley Hall feeds Moreton Mill, and flows thence to the River Duckow. Other streams flow south through Ashford Grange to the Bailey brook above, and the two systems are linked near Wyrley, through which village the parting passes west and north towards Ightfield. The condition of affairs in this district is by no means clear on the ½-inch maps, but can be better understood by reference to the 1-inch maps 138 and 139.

Bishop's Wood.—The wood itself lies on sloping ground, the high levels being on the south and east sides. The stream which flows through the village of Adbaston receives water from the neighbourhood of Wood Farm, and the water-parting lies on the north side of the high-road from Doley to Bishop's Offley. At Bishop's Offley village the ground falls rapidly towards the Offley brook on the north, and by a gentle gradient east and west of the village. Between the north and south woods there is a marsh, which is crossed by the water-parting between two spurs, both easily visible from the wood south of Fair Oak.

Ellesmere.—At Bettisfield, east of Ellesmere, the point at which the water-parting crosses the railway is coincident with the cutting marked on the 1-inch map (sheet 138). The stream flowing south near here is the River Roden, which lies within the basin. From this point the parting can be traced in a north-western direction round Breaden Heath, and across the railway-line twice near Crimpsfield, the line here being in a cutting for about 1 mile. The meres to the south are in the main spring-fed, and each one of them lies in a deep hollow surrounded by high

ground. They serve to feed the Shropshire Union canal; but there is no natural outlet on the northern side. West of Ellesmere, the water-parting is easily located at Elson, and can be traced without difficulty to St. Martin's. In this village, near Cross Lanes, a dry stream-bed was sufficiently evident to be followed down to the canal-side. Its direction fixes the water-parting on high ground near Wigginton, and thence on a slight spur down to the canal. A continuous artificial drainage runs parallel to the canal on its north side. The drains were dry, but were traced westward, and seem to connect with the Morlas brook. The exact position at which the parting crosses the canal appears to lie between two spurs, one of which leads up to high ground at Wigginton as explained, while the second rises to the cross roads near Hentle Hall. West of this point, a ridge can be followed west and south, passing north of Upper Hengoed, and joining with the portion already fixed on the maps at Cross Lanes, south of Selattyn.

Church Stretton.—The railway-line at Church Stretton lies in a valley which receives streams from mountainous country on either side, and which drains partly to the north-east and partly to the north-west. The parting between the two systems of drainage is not clear from the maps, but on inspection was found to cross the valley at or near Church Stretton station. Hence it was followed up into the hills on either side without difficulty until it joined with clearly defined ridges at Hope Bowdler Hill on the east, and at Pole Bank on the west.

Fallerdig Carno.—The moorlands near Fallerdig are of such a nature as to define the parting with considerable exactness. In this case, however, the land-marks were so few that location of the points of observation was difficult.

Wolverhampton.—At Wolverhampton the supposed line of the water-parting was found to have been placed too near the canal near Tettenhall. The main road to Tettenhall falls rapidly on either side of the canal to the bridge by which it crosses the canal. There is a stream flowing south-west in this valley, and the water-parting is easily located on the high ground north and west of Tettenhall parish church, and followed from this position as far as Perton. It was at first thought to cross the canal near the racecourse, and to pass through Wolverhampton; the centre of this town lying on high ground. By tracing a stream from Dunstall Hall to Showell Farm, it became evident that the water-parting followed a line further north as far as Bushbury Hill, and then turned south to enter Wolverhampton on the east side where it passed over the hill summit and south towards Sedgeley.

The total area of the basin above Worcester was measured by planimeter on the ½-inch maps, and determined to be 1970·67 square miles.

The inter-contour areas of the Severn basin above Worcester were independently measured with the following result:—

Feet.	Square miles.	Per cent.
Above 2500	0·20	0·01
2500–2250	0·56	0·03
2250–2000	2·24	0·10
2000–1750	11·96	0·61
1750–1500	25·24	1·30
1500–1250	85·00	4·31
1250–1000	126·00	6·39
1000–800	148·84	7·55
800–600	193·72	9·83
600–400	352·12	17·87
400–200	848·36	43·05
Below 200	176·40	8·95
	1970·64	100·00

REPORT ON SUSPENDED AND DISSOLVED MATTER IN THE EXE, CREEDY, SEVERN, AND MEDWAY.

By A. STRAHAN, Sc.D., LL.D., F.R.S.

A DETERMINATION of the suspended and dissolved impurities carried by the rivers was one of the primary objects of this investigation. Arrangements were therefore made for the collection of samples of water as frequently as possible, and especially at such times as to be representative of all conditions of the rivers, so far as that was practicable.

Experiments were made in the first place as to the desirability of collecting samples at different depths, and a form of bottle was devised which could be lowered into the water closed, but opened and closed again at any desired depth. The difficulty of working the apparatus in a strong stream proved great, and it did not appear that any appreciable advantage was gained by its use. Subsequently, therefore, all samples were collected by dipping up water from a foot or two below the surface, from any point well out in the stream, either from a bridge, a jetty, or a boat. The examination of the water was limited to a determination of the amount of suspended and dissolved matter. It was undertaken in the case of the Exe and Creedy by Mr. W. H. Lewis, of the University College, Exeter; in the case of the Medway by Mr. R. C. Wills, of the Technical Institute at Gillingham, and subsequently by Mr. A. N. Fitzgerald, and in the case of the Severn by the late Dr. G. H. Woollatt and Mr. C. W. Marshall. We are greatly indebted to these gentlemen for their performance of this laborious task, which generally included the collecting of the samples themselves.

In the following account the observations on the four rivers have all been treated in the same way. Firstly, the actual records are given in tabular and graphic form. Secondly, the average amounts of suspended and dissolved matters are shown for various heights of the rivers on a separate graphic figure. For while the records were being gathered it became apparent that the proportion of neither suspended nor dissolved matter was constant in relation to the height of the river. This might be due to various causes, and amongst others to artificial interference, for the rivers traverse cultivated and thickly populated regions. It seemed inadvisable, therefore, to generalize from single observations (except possibly in such cases as floods, when the effects of artificial interference would probably be swamped), and to place more reliance on the average results at various heights of the river.

THE EXE AT BRAMPFORD SPEKE.

The results obtained by Mr. W. H. Lewis from his examination of the Exe water are shown in Table XXXV., and in graphic form in Fig. 14. The samples were collected at Brampford Speke, but were not got without difficulty, for the Exe varies in discharge so rapidly that the proper moment for collecting a sample had usually passed before the journey of 4 miles from Exeter could be accomplished. Latterly the services of a man living on the river-bank were secured, and a number of samples collected, which there is no reason to doubt were fair representatives of the water.

It would be anticipated that the amount of suspended matter carried by the

water would rise as the height and velocity of the river increased, but that the amount of dissolved matter would rise as the height of the river decreased, and as the supply of water was derived more and more from springs. In the following remarks I have used the term "normal" as indicating that the behaviour of the lines for suspended and dissolved matter is in agreement with this anticipation.

The proportion of suspended matter is shown in Fig. 14 to be in close sympathy with the height of the river. With one exception (January 9, 1912) it rises as the river rises. It is, therefore, in accordance with expectation and "normal." Generally the amount is small; in fact, the suspended matter contained in 1 gallon of water was "not measurable" for low gauge-readings. In floods the amount goes up with a rush, as on October 16, 1909, March 5 and 15, 1912.

The proportion of dissolved matter is small as compared with the other rivers investigated. It is, moreover, "abnormal" in the sense that it rises with a rising river. If we analyze the observations on the assumption that the proportion of dissolved matter should normally vary inversely as the level of the river, we find that on sixteen dates the line is abnormal, namely, in 1911, on December 23 and 29; in 1912, on January 1, 5, 9, 12, 23, 26, 30, February 6, 9, March 1, 5, 8, 19, 22, while on twelve dates it is normal, namely, in 1907, May 7, June 12, 27; in 1912, February 2, 12, 16, 20, 23, 27, March 12, 15, 29.

In Fig. 15 the averages given in the following table are graphically plotted:—

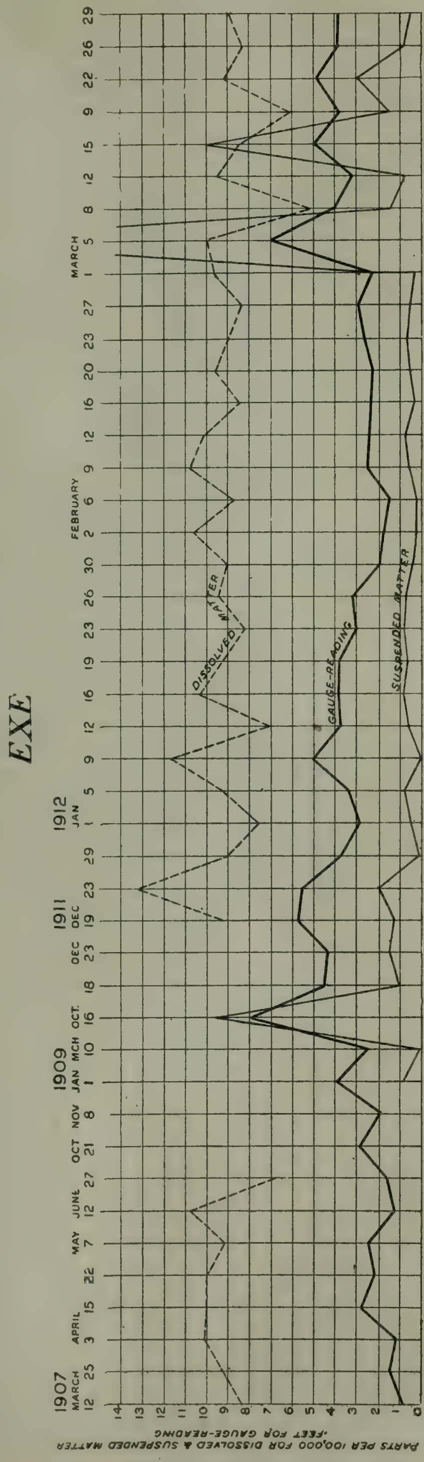


FIG. 14.

Gauge-readings.	Average of gauge-readings.	Suspended matter. Parts per 100,000.	Dissolved matter. Parts per 100,000.
Inches.	Inches.		
0–11	0·90 (1)	nil (1)	8·400 (1)
12–23	16·56 (7)	·080 (7)	9·430 (6)
24–35	28·80 (14)	·425 (14)	9·327 (12)
36–47	42·60 (11)	·783 (11)	8·690 (11)
48–59	50·16 (5)	1·575 (5)	7·200 (2)
60–71	64·20 (4)	4·350 (4)	10·650 (4)
72 and more	89·40 (2)	17·200 (2)	10·000 (1)

The figures in brackets show the number of observations on which the average is founded.

In Fig. 15 the line for suspended matter shows that the river carries but little until it reaches a level of 50 inches, but that on exceeding that height it increases rapidly in transporting power. The Exe may be described as a vivacious river; it is not canalized, and at Brampford Speke is not controlled by weirs.

TABLE XXXV.

Suspended and Dissolved Matter in the Exe at Brampford Speke.

By W. H. LEWIS.

		Gauge-reading.		Suspended matter. Parts per 100,000.	Dissolved matter. Parts per 100,000.			Gauge-reading.		Suspended matter. Parts per 100,000.	Dissolved matter. Parts per 800,000.
		ft.	ins					ft.	ins.		
1907	Mar. 12		9	nil	8·4	1912	Jan. 16	3	9	·95	10·4
,,	,, 25	1	5	,,	9·2	,,	,, 19	3	8	·76	9·3
,,	April 3	1	3	,,	10·04	,,	,, 23	3	0	·82	8·2
,,	,, 15	2	9	,,	10·00	,,	,, 26	3	1	·645	9·4
,,	,, 22	2	3	,,	10·00	,,	,, 30	2	1	·43	9·0
,,	May 7	2	5	,,	9·2	,,	Feb. 2	1	10	·25	10·6
,,	June 12	1	3	,,	10·8	,,	,, 6	1	5	·23	8·8
,,	,, 17	1	6	,,	6·8	,,	,, 9	2	5	·623	10·8
,,	Oct. 21	2	8	,,		,,	,, 12	2	4	·75	10·2
,,	Nov. 8	1	9	,,		,,	,, 16	2	3	·40	8·48
1909	Jan. 1	4	0	·89		,,	,, 20	2	2	·514	9·6
,,	Mar. 10	2	5	nil		,,	,, 23	2	6	·747	9·04
,,	Oct. 16	7	9	·96		,,	,, 27	2	9	·58	8·4
,,	,, 18	4	5	1·07		,,	Mar. 1	2	3	·453	9·6
,,	Dec. 23	4	3	1·465		,,	,, 5	7	0	24·8	10·0
1911	Dec. 19	5	7	1·3	9·4	,,	,, 8	4	0	1·55	5·2
,,	,, 23	5	6	2·0	13·2	,,	,, 12	3	2	·83	9·44
,,	,, 29	3	11	·077	9·0	,,	,, 15	5	0	10·0	8·4
1912	Jan. 1	2	8	·6	7·6	,,	,, 19	3	8	1·5	6·24
,,	,, 5	3	3	·8	9·2	,,	,, 22	4	11	2·9	9·2
,,	,, 9	5	1	·1	11·6	,,	,, 26	3	10	·96	7·84
,,	,, 12	3	8	·645	7·6	,,	,, 29	3	9	·55	8·96

The line for dissolved matter is fairly constant in level, but is slightly higher for the highest water-levels than it is for the lowest, and is therefore abnormal. In this respect the Exe differs from the other rivers examined. For gauge-readings up to 50 inches the curve is about what might have been expected, but the abnormality is apparent in the last two columns. No doubt it would be modified if more observations were available, but the association of a rising proportion of dissolved matter with a high river is too frequent to be set aside.

TABLE XXXVI.

THE EXE AT BRAMPFORD SPEKE.

Total load of Suspended and Dissolved Matter at all heights of the river.

	Gauge-readings in inches.	No. of days.	Total volume in millions of cubic feet.	Suspended matter. Parts per 100,000.	Total do. in tons.	Dissolved matter. Parts per 100,000.	Total do. in tons.
1907	0-11	73	735·1	nil	nil	8·4	1720·96
	12-23	184	5090·3	·08	113·49	9·43	13378·3
	24-35	75	4150·6	·425	591·64	9·327	10789·4
	36-47	22	2019·5	·783	440·70	8·69	4891·13
	48-59	4	579·6	1·575	254·42	7·2	1163·07
	60-71	4	724·0	4·35	877·75	10·65	2148·98
	72-83	3	668·6	10·0 *	1863·43 *	10·0 *	1863·43*
	84-95	—	—	—	—	—	—
		365	13967·7		4141·43		35955·27
1908	0-11	110	872·8	nil	nil	8·4	2286·59
	12-23	179	5118·3	·08	114·12	9·43	13451·99
	24-35	63	3526·1	·425	417·66	9·327	9166·0
	36-47	12	1015·5	·783	221·61	8·69	2459·5
	48-59	2	277·9	1·575	121·99	7·2	557·66
		366	10810·6		875·38		27921·74
1909	0-11	157	1365·1	nil	nil	8·4	3195·87
	12-23	102	2732·5	·08	60·9	9·43	7181·5
	24-35	56	3272·5	·425	387·59	9·327	8506·03
	36-47	34	3121·5	·783	681·35	8·69	7560·12
	48-59	8	1071·5	1·575	470·3	7·2	2149·95
	60-71	2	360·5	4·35	437·06	10·65	1070·04
	72-83	4	898·6	10·0 *	2504·45 *	10·0 *	2504·45*
	84-95	2	613·4	17·2	2940·47	10·00	1709·58
		365	13435·6		7482·12		33877·54
1910	0-11	74	792·1	nil	nil	8·4	1854·4
	12-23	138	3614·9	·08	80·60	9·43	9500·65
	24-35	52	3196·1	·425	278·58	9·327	8308·2
	36-47	66	6186·1	·783	1349·97	8·69	14982·4
	48-59	18	2448·1	1·575	1074·93	7·2	4913·95
	60-71	12	2196·4	4·35	2662·84	10·65	6519·38
	72-83	3	682·8	10·0 *	1903·00 *	10·0 *	1903·00*
	84-95	2	560·0	17·2	2684·5	10·0	1560·75
		365	19676·5		10034·42		49542·73
1911	0-11	188	1112·8	nil	nil	8·4	2605·2
	12-23	80	2504·9	·08	55·85	9·43	6583·36
	24-35	51	2952·8	·425	349·76	9·327	7675·8
	36-47	21	1888·6	·783	412·14	8·69	4574·1
	48-59	10	1403·3	1·575	615·99	7·2	2815·97
	60-71	13	2332·5	4·35	2827·85	10·65	6923·35
	72-83	—	—	—	—	—	—
	84-95	2	545·4	17·2	2614·5	10·0	1520·06
		365	12740·3		6876·09		32697·84
1912 Jan.–Mar.	0-11	—	—	nil	nil	8·4	—
	12-23	6	202·9	·08	4·52	9·43	533·26
	24-35	41	2368·7	·425	280·57	9·327	6157·4
	36-47	29	2752·2	·783	600·6	8·69	6665·7
	48-59	8	1128·6	1·575	495·41	7·2	2264·74
	60-71	4	666·7	4·35	808·28	10·65	1978·9
	72-83	2	412·9	10·0 *	1150·77 *	10·0 *	1150·77*
	84-95	1	270·3	17·2	1295·74	10·0	753·34
		91	7802·3		4635·89		19504·11

* Estimated.

In the preceding table the number of days in the year at which the gauge-reading lay between 0 and 1 foot, 1 foot and 2 feet, etc., is given, and against these are placed the averages of the determinations of suspended and dissolved matter. From these data the number of tons carried in the year for each gauge-reading have been calculated for me by Dr. H. H. Thomas. It will be noticed that, in spite of the small number of days on which the river reached the high levels, a far greater quantity of suspended matter was carried during those days than during the long period of low water, but that, on the other hand, the bulk of dissolved matter was carried during those long periods when the river was at a normal level. The number of tons estimated to have been carried during the period of observation are given below.

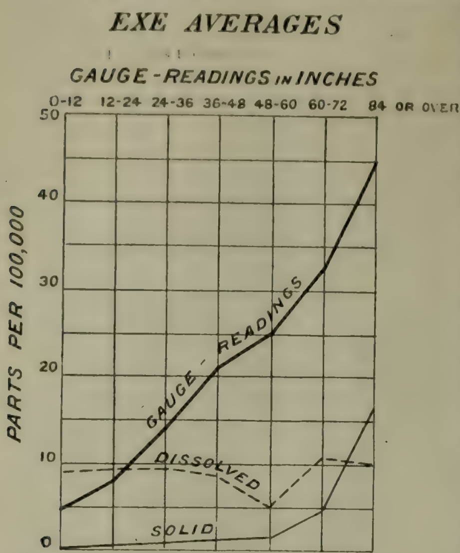


Fig. 15.

TABLE XXXVII.

The Exe at Brampford Speke.

	Total volume of water in millions of cubic feet.	Total suspended matter in tons.	Total dissolved matter in tons.
In 1907	13967·7	4141·43	35955·27
„ 1908	10810·6	875·38	27921·74
„ 1909	13435·6	7482·12	33877·54
„ 1910	19676·5	10034·419	49542·73
„ 1911	12740·3	6876·09	32697·84
„ 1912, January–March ...	7802·3	4635·89	19504·11
Total in 5¼ years ...	—	34045·329	199499·23

The Exe.

The Amount rolled along the Bottom.

The determination of the amount rolled by a river along the bottom of the channel presents a problem wholly different to that presented by matter in suspension or solution. Various devices have been suggested for the determination, but so far as I am aware, the only reliable measurements are those obtained by dredging operations conducted over a number of years. Dredging is conducted in order to keep the channel constant in section. Where this object is attained the amount dredged is the amount brought in and left by the river.

We have been fortunate in obtaining through the kindness of Mr. Thomas Moulding, City Surveyor of Exeter, some highly significant records. The dredging is conducted in a length of the river close above Exeter, in which the water is held up at a constant level by a weir and is kept at a constant depth as a bathing place by removing the gravel as fast as it accumulates. It may be assumed that no gravel

is rolled over the weir. The amount dredged is therefore the amount which the river rolls on to this part of its course. Mr. Moulding remarks that there is no doubt that the dredging has been going on from twenty to twenty-five years, but that his own records go back only to 1904.

The dredgings for	1904	were	1690	cubic yards
,,	1905	,,	1576	,,
,,	1906	,,	1388	,,
,,	1907	,,	892	,,
,,	1908	,,	892	,,
,,	1909	,,	1423	,,
,,	1910	,,	210	,,
Total in seven years was			8071	,,

The average quantity dredged annually during the seven years amounts, therefore, to 1153 cubic yards, and this presumably represents the average amount of material rolled along the bottom of the river and deposited annually in the bathing place. The dredgings consist of about 50 per cent. of large stones, say 3 inches in diameter; 40 per cent. of stones, varying from 2 inches diameter to the size of a pea; and about 10 per cent. varying from the size of a pea to fine sand.

The Creedy.

Here, also, the collecting of samples gave trouble. A visit to the Exe and the Creedy on the same day involved a long round and increased delay. The assistance of a gardener, whose employment lay close to the river, was therefore called in, but the muddiness of some of the samples sent in by him led to a suspicion that insufficient care was exercised, and the collecting was subsequently done by Mr. Lewis' assistant, whenever his other duties permitted it. The samples were got from midstream by lowering a bottle from a bridge. The suspected samples have been discarded, and those collected by Mr. Lewis' assistant distinguished by a footnote.

TABLE XXXVIII.

Suspended and Dissolved Matter in the Creedy at Cowley Bridge.

By W. H. LEWIS.

		Gauge-reading.		Suspended matter. Parts per 100,000.	Dissolved matter. Parts per 100,000.			Gauge-reading.		Suspended matter. Parts per 100,000.	Dissolved matter. Parts per 100,000.
		ft.	ins.					ft.	ins.		
1907	Mar. 17	3	0	nil.	17·6	1912	Feb. 9	4	0	5·10	14·8
,,	(?)	3	6	,,	23·2	,,	,, 12‡	3	7	1·96	17·0
,,	Apr. 16	3	0	,,	22·0	,,	,, 16	3	6	1·00	16·4
,,	May 15	3	5	,,	16·0	,,	,, 23	3	6	3·15	17·12
,,	June 1	3	6	0·56*	15·2	,,	Mar. 1	3	6	7·50	19·28
,,	July 8	3	0	nil.	15·6	,,	,, 4‡	4	0	14·00	11·6
,,	Nov. 4	4	5	5·40†	13·2	,,	,, 8	4	6	3·50	15·36
1909	Mar. 10	4	5	14·6	nil	,,	,, 11‡	3	10	2·96	15·6
,,	Dec. 23	7	0	52·4	,,	,,	,, 15	4	10	11·18	6·0
1911	,, 19	5	4	5·62	14·62	,,	,, 18‡	4	0	1·96	17·0
,,	,, 27	4	8	8·20	12·8	,,	,, 22	5	1	6·80	13·92
1912	Jan. 26‡	4	0	1·55	12·0	,,	,, 25‡	4	5	2·27	11·0
,,	,, 26‡	4	0	1·20	14·2	,,	,, 29	3	6	1·22	15·8
,,	Feb. 2‡	3	3	1·73	20·0	,,	Apr. 4	3	4	·83	24·8
,,	,, 5‡	3	1	1·00	19·0						

* Calculated from the sediment of six Winchester bottles full of water.

† Calculated from the sediment of one Winchester bottle full of water, dried at 110° C. The sediment seemed to be chiefly organic.

‡ Samples collected by Mr. Lewis' assistant.

CREEDY.

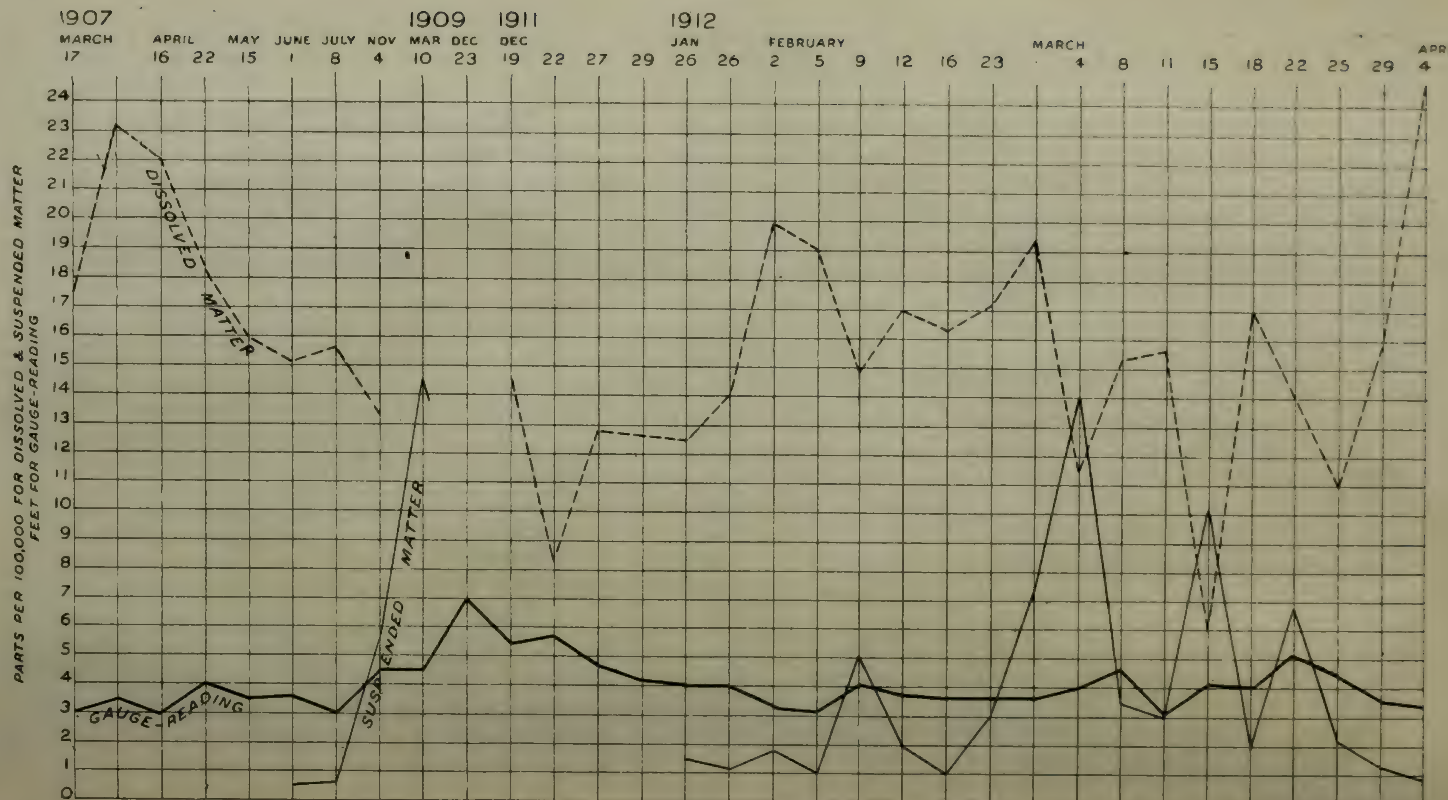


FIG. 16.

The observations shown in the table are plotted graphically in Fig. 16, except that the highest amount of suspended matter, found on December 23, 1909, at the time of the highest gauge-reading, is not inserted for want of space. There is generally a sympathy between the two lines, except on March 8, 1912, when a rise of the river is accompanied by a marked fall in the suspended matter. The line is generally normal.

Dissolved matter is at its highest when the river is at its lowest, as in March, 1907, February, March, and April, 1912. In several cases the amount falls conspicuously in response to a rise of river, as November 4, 1907, December 22, 1911, February 9, March 4 and 15, 1912, while examples of the reverse are rare. The curve for dissolved matter may therefore be described as normal, in the sense that it rises as the discharge diminishes.

In Fig. 17 the averages given in the table below form the data for the curves.

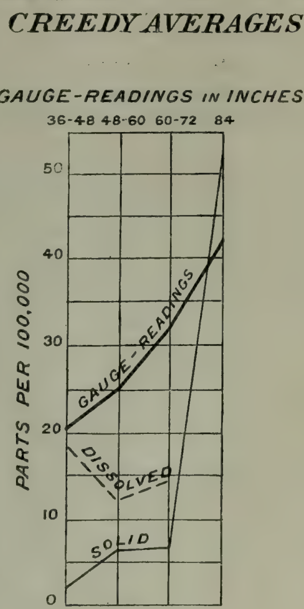


FIG. 17.

Great activity as regards the carrying of matter in suspension commences on the Creedy with readings between 72 and 84, that is with the river at 3 to 4 feet above summer flow. On the Exe it commences with the river at 6 to 7 feet above summer flow.

Gauge-readings.	Average of gauge-readings.*	Average suspended matter.	Average dissolved matter.
Inches.	Inches.	Parts per 100,000.	Parts per 100,000.
36–47	41·28 (15)	2·19 (10)	18·30 (15)
48–59	51·24 (11)	6·27 (11)	12·79 (10)
60–71	63·00 (2)	6·21 (2)	14·26 (2)
72–	84·00 (1)	52·40 (1)	

The figures in brackets show the number of observations upon which the average is founded.

The Severn at Worcester.

The periodical examination of the water of the Severn was kindly undertaken by the late Dr. G. H. Woollatt, with the assistance of Mr. C. W. Marshall, at the Victoria Institute, Worcester. Observations were commenced in February, 1909, and continued till March, 1910, when they were interrupted by pressure of other work. In January, 1912, they were resumed, and an almost continuous series of daily observations was maintained.

The earlier samples were collected from a boat taken out into the centre of the stream, by immersing a large bottle suddenly to a depth of 6 inches below the surface. In 1912 the samples were taken at the end of a raft, at a spot about one quarter across the river. About 2 litres of water were found to be sufficient, and the weighings were taken to four places of decimals. The height of the river was read at the waterworks gauge at the time of taking the samples.

* From simultaneous readings of the gauges on the Creedy and the Exe (at Brampford Speke) it may be calculated that a reading of 36 inches on the Creedy gauge corresponds to one of 12 inches on the Exe gauge.

TABLE XXXIX.

SUSPENDED AND DISSOLVED MATTER IN THE SEVERN AT WORCESTER.

By Dr. G. H. WOOLLATT and C. W. MARSHALL.

		Gauge-reading. ft.	ins.	Suspended matter in parts per 100,000.	Dissolved matter in parts per 100,000.	Remarks.
1909	Feb. 4, 3.30 p.m.	1	7	0·40	31·2	Moderate, clear.
,,	,, 11, 3.15 ,,	2	4	0·43	32·4	Rapid.
,,	Mar. 4, 3.15 ,,	1	1	0·39	41·6	Sluggish.
,,	,, 10, 4.0 ,,	1	7	3·24	36·4	Slow.
,,	,, 17, 3.20 ,,	1	6	0·83	40·8	,,
,,	,, 24, 3.16 ,,	1	10	5·14	30·2	Moderate.
,,	,, 26, 3.0 ,,	4	9½	19·76	22·0	Very rapid, rough.
,,	,, 31, 3.15 ,,	2	10	2·40	22·6	Rapid.
,,	April 21, 3.15 ,,	2	4	3·20	28·2	,,
,,	,, 28, 3.15 ,,	2	8	1·77	20·2	,,
,,	May 5, 3.15 ,,	1	8	2·00	24·0	Moderate.
,,	,, 12, 3.15 ,,	1	0	1·24	35·0	Slow.
,,	,, 19, 3.15 ,,	0	10	2·68	46·2	,,
,,	,, 26, 3.15 ,,	0	10	4·64	45·4	,,
,,	June 9, 3.15 ,,	0	9	0·56	42·6	,,
,,	,, 23, 3.15 ,,	0	8¾	0·54	52·4	,,
,,	July 8, 7.30 ,,	0	10	1·18	43·0	,,
,,	,, 22, 8.0 ,,	0	9	0·16	36·6	,,
,,	Aug. 5, 8.0 ,,	0	11	2·76	39·8	,,
,,	,, 18, 6.50 ,,	0	7½	2·0	45·4	,,
,,	Sept. 15, 4.15 ,,	0	8	2·04	44·4	,,
,,	,, 29, 3.0 ,,	1	4	10·16	67·0	Moderate.
,,	Oct. 13, 2.45 ,,	3	10	15·4	19·98	Rapid.
,,	,, 28, 3.15 ,,	3	7½	3·0	19·0	,,
,,	Nov. 11, 3.0 ,,	1	0	2·98	34·8	Slow.
,,	,, 25, 3.0 ,,	0	10	1·06	44·5	,,
,,	Dec. 9, 3.15 ,,	3	4	3·26	23·8	Rapid.
1910	Jan. 13, 3.15 ,,	3	11	0·5	21·2	,,
,,	,, 27, 3.15 ,,	2	8	1·68	27·8	Moderate.
,,	Feb. 10, 3.45 ,,	3	8	5·18	24·6	Rapid.
,,	,, 24, 3.15 ,,	5	5	4·06	21·0	Very strong.
,,	Mar. 10, 3.0 ,,	3	6	3·98	32·4	Rapid.
1912	Jan. 16, 9.0 a.m.	3	8	—	—	
,,	,, 17, 9.0 ,,	3	9	—	—	River rising. Rain during night. Snow began to fall at noon.
,,	,, 17, 3.15 p.m.	5	4	19·44	25·0	
,,	,, 18, 9.30 a.m.	8	0	6·46	30·4	Total snowfall 12 inches.
,,	,, 19, 9.30 ,,	8	5	4·68	27·4	Dry.
,,	,, 20, 9.30 ,,	6	10	2·96	28·6	Thaw, slight rain.
,,	,, 21, 9.0 ,,	8	11	—	—	Thaw.
,,	,, 22, 9.30 ,,	10	5	1·28	31·8	Frost commences.
,,	,, 23, 9.30 ,,	9	3	1·06	27·2	Frosty morning. Rain, snow, and thaw later.
,,	,, 24, 9.30 ,,	8	10	3·22	29·2	Rapid thaw.
,,	,, 25, 9.0 ,,	8	11½	—	—	Cold, slight thaw.
,,	,, 26, 9.30 ,,	7	5	1·58	28·6	Very slight frost. Thaw continuing in parts.
,,	,, 27, 9.0 ,,	5	9	—	—	Do.
,,	,, 28, 9.30 ,,	3	8	1·54	33·4	Hard frost.
,,	,, 29, 9.0 ,,	2	8	—	—	,,
,,	,, 30, 9.30 ,,	2	4	1·08	34·4	Frost in morning, thaw later.
,,	,, 31, 9.0 ,,	2	2	—	—	Snow mostly gone.

It was noticed by Dr. Woollatt in 1910 that neither the rapidity of the stream, nor the colour of the water as judged by eye, was proportional to the height on the gauge. Frequently the muddiness of the water varied, though there was no variation in the gauge-reading, while in some cases the amount of suspended matter increased on a falling river. These anomalies may probably be attributed to the fact that the Severn is a canalized river. It is subject to artificial and local changes in rapidity of flow, and to interference with natural conditions of the water in its course through a populous and cultivated country.

The observations are plotted in Fig. 18. In this figure the record of January, 1912, is separated from the previous records for the reason that it was a period of snow, frost, rain, and thaw. We will first consider the results obtained in 1909 and 1910.

The line for suspended matter rises and falls in general sympathy with the line for gauge-readings. It rises high for high gauges on March 26 and October 13, 1909, and is generally low for low gauges. Exceptions occur on April 21, 28, and May 26, 1909, and on January 13 and February 24, 1910.

The line for dissolved matter, which appears likely to have been the least affected by artificial interference, gives a fairly definite result. In February and the early part of March, 1909, the river was low and the dissolved matter high. On March 26 the river rose and the dissolved matter conspicuously fell. From May to September the river was low and the dissolved matter persistently high, but in October, when the river rose, the dissolved matter reached its lowest. The line, therefore, is normal in the respect that it varies inversely as the height of the river.

In January, 1912, abnormal conditions prevailed, and an opportunity of observing the effect of a fall of snow upon the solids carried by the river was promptly taken by Dr. Woollatt and Mr. Marshall. They report that "the height of the river was normal at the commencement of the snowfall. The fall of snow was preceded by a downfall of rain; hence the first snow to fall was rapidly dissolved and the river rose with great rapidity, as will be seen from the following data :—

	Feet.	Inches.	
January 16, 9.0 a.m.	3	8	on gauge.
,, 17, 9.0 a.m.	3	9	,,
,, ,, 3.15 p.m.	5	4	,,
,, 18, 9.30 a.m.	8	0	,,

Snow fell heavily during the 17th and 18th, and total snowfall exceeding 1 foot seems to have been general for the district.

"After the first rapid rise the water fell 19 inches on the 20th, but on this day there commenced a thaw lasting for two days which resulted in a rapid rise. Frosty weather following causes a gradual decline on the two following days, but a rapid thaw on the 24th increases the height on the morning of the 25th. After this date frosty weather was general, the snow only slowly disappeared, and the level falls daily."

The observations made during the period January 16–31 are recorded in the right-hand part of Fig. 18. The record commences with a low river on the 16th, and shows the rapid rise to the 18th. The suspended matter on the 17th is at its maximum. The water, except for the fall noted on the 20th, continues to rise till it reaches its maximum on the 22nd; the suspended matter simultaneously falls almost to its minimum. On the 24th the river has fallen, but the suspended matter has risen. Subsequently a steady fall of the river sets in, and is accompanied by a steady fall in the suspended matter. The line for suspended matter is therefore abnormal during the period January 18–27, and even after that is lower than would have been expected.

SEVERN

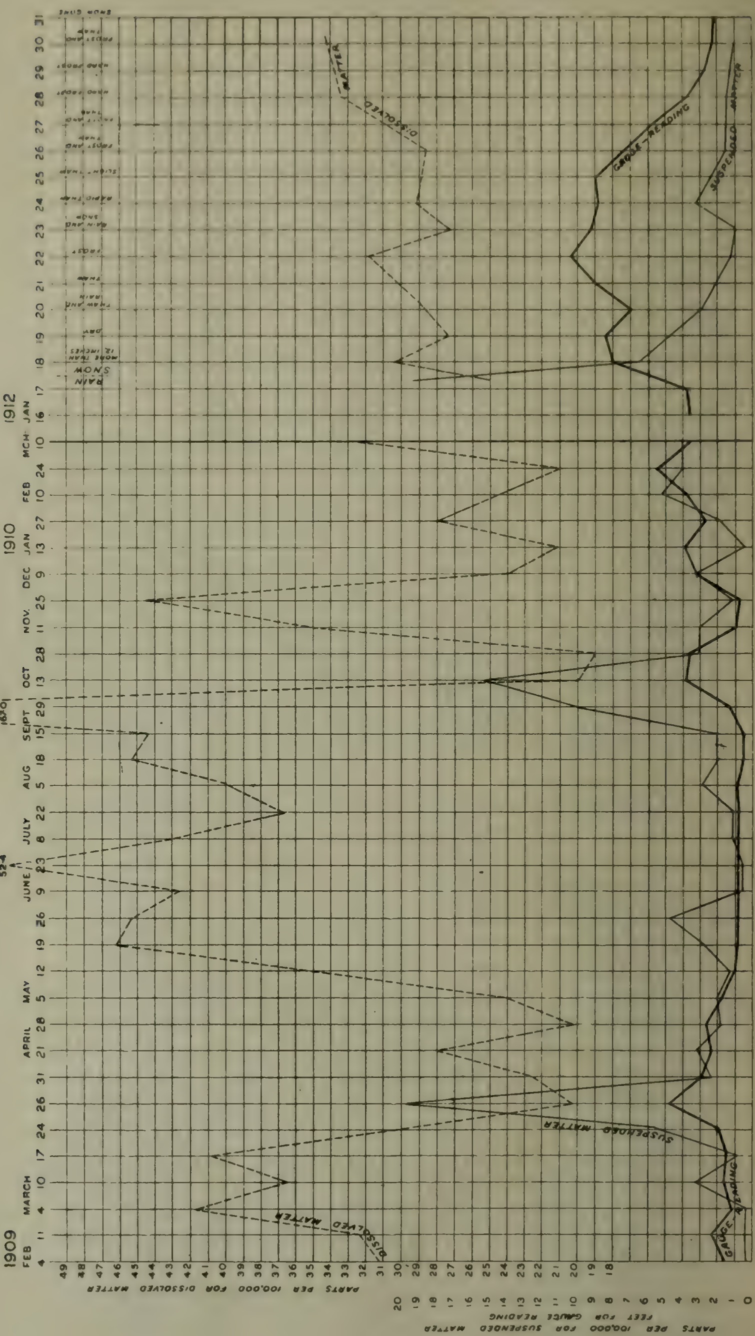


Fig. 18.

The line for dissolved matter commences normally, but rises on the 18th, when normally it should have fallen. It behaves abnormally on the 22nd and 23rd through the height of the flood, but gradually tends to become normal as the river regains its usual level. In the lines both for suspended and dissolved matter abnormality commences when the ground is covered with snow, and dies away gradually as the snow disappears. No abnormality is caused by hard frost on the 28th and 29th.

In Fig. 19 the averages are plotted for all readings, the actual values being given in the following table:—

Average of gauge-readings.	Suspended matter.	Dissolved matter.
Inches	Parts per 100,000.	Parts per 100,000.
9·28 (10)	1·76 (10)	44·03 (10)
16·77 (9)	2·93 (9)	37·88 (9)
30·33 (6)	1·76 (6)	27·60 (6)
43·78 (7)	4·69 (7)	24·91 (7)
62·17 (3) *	14·42 (3) *	22·67 (3) *
100·00 (7) †	3·03 (7) †	29·03 (7) †

The figures in brackets show the number of observations on which the averages are based.

Excluding for the moment consideration of the last column in Fig. 19, the lines are generally normal. Though suspended matter is less for gauge-readings of 24–36 inches than it is for gauge-readings of 12–24, the difference is small and well within the limits of experimental error. As a fact the difference is almost wholly due to a reading on September 29, 1909, when 10·16 parts per 100,000 of suspended matter occurred with a gauge-reading of 16 inches. But for this exceptional observation the average in the second column would have fallen nearly in line with those on the first and third columns, and the irregularity may well have been due to some local and temporary interference with the character of the water. There is a slow rise up to readings of 36–48 inches, but for higher gauge-readings the rise is abrupt. Great activity as regards carriage of suspended matter appears to commence when the level of the water is about 4 feet above lowest readings. The line for dissolved matter is normal in that it falls as the river rises. The average amount is greater in all conditions of the river than it is in either the Exe, the Creedy, or the Medway.

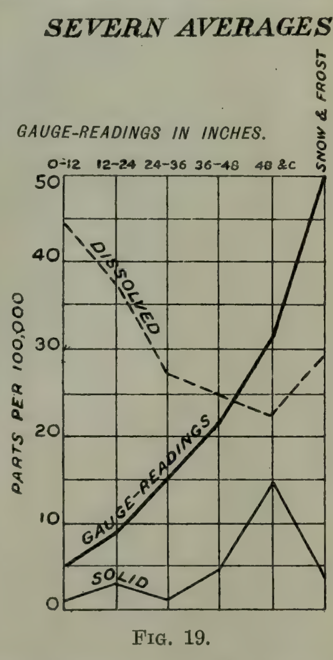


FIG. 19.

Turning now to the last column in Fig. 19 we find a reversal of the lines both of suspended and dissolved matter. The highest gauge readings coincide with low readings in suspended matter, and with an increasing

* Including an observation made at 3.15 p.m. on January 17, three hours after snow had commenced to fall, but before the ground was covered.

† Founded on the observations made on January 18–26, 1912, inclusive.

reading in dissolved matter. Abnormality sets in with a fall of snow and lasts till the snow has gone.

The Medway at Allington.

The observations on the suspended and dissolved matters in the Medway are tabulated below and plotted in Fig. 20. For the reasons stated on p. 19 it has not been possible to give a discharge-curve. The figure serves, however, for comparison with the Exe and Severn as regards the amount carried. The amount carried in suspension is greater than in either of those rivers, while the amount in solution is greater than that in the Exe, but smaller than that in the Severn.

Suspended and Dissolved Matter in the Medway at Allington, by Mr. R. C. Wills and Mr. A. V. Fitzgerald.

		Suspended matter.	Dissolved matter.			Suspended matter.	Dissolved matter.
		Parts per 100,000	Parts per 100,000.			Parts per 100,000.	Parts per 100,000.
1908	June 16, 11.15 a.m.	*nil*	24·38	1910	Jan. 8, noon	0·4	27·5
,,	Aug. 29, noon	*nil*	22·54	,,	,, 22, 3.15 p.m.	0·9	21·9
1909	April 24, 11.50 a.m.	0·9	24·46	,,	Feb. 5, noon	6·6	26·25
,,	May 7, 7.45 p.m.	1·2	26·68	,,	,, 19, noon	8.9	28·5
,,	,, 22, 11.15 a.m.	0·34	24·12	,,	Mar. 4, 7.30 a.m.	0·7	22·6
,,	June 4, 7.20 p.m.	0·15	25·34	,,	,, 19, 12.15 p.m.	3·1	26·1
,,	,, 18, 7.45 a.m.	0·35	24·23	,,	April 16, 12.15 p.m.	5·9	24·4
,,	July 3, noon	0·34	25·77	,,	May 21, 11 a.m.	14·1	19·3
,,	Oct. 16, 12.40 p.m.	3·5	26·9	,,	June 16, 3.25 p.m.	5·17	27·3
,,	,, 23, 12.30 p.m.	5·3	26·35	,,	,, 25, 9.35 a.m.	8·9	27·0
,,	,, 28, noon	5·65	20·9	,,	July 6, 11.45 a.m.	16·3	28·3
,,	Nov. 13, 12.15 p.m.	0·7	27·1	,,	,, 23, 12.15 p.m.	6·8	27·5
,,	,, 27, 11.50 a.m.	3·3	29·1	,,			
,,	Dec. 10, 4 p.m.	1·0	25·7				
,,	,, 23, 2.15 p.m.	13·02	21·73				

Summary.

Taking the average of all observations on the four rivers we get the following table:—

	Suspended matter in parts per 100,000.	Dissolved solids in parts per 100,000.
The Exe	1·36 (44)	9·17 (37)
The Creedy	5·76 (27)	15·41 (27)
The Severn	3·62 (42)	33·25 (42)
The Medway...	4·24 (27)	25·26 (27)

The figures in brackets show the number of observations.

It appears from the diagrams that the rise in the amount of suspended matter carried is rapidly accelerated when the water reaches a certain level. In the Exe the acceleration appears when the gauge readings exceed 50 inches, in the Severn it appears when the gauge-readings exceed 44 inches. This "critical level" is not rigidly defined, but may be regarded as indicating a velocity of current which is sufficient to carry particles of appreciable size and to effect the erosion in parts of the channel which are stable at lower velocities. The discharge of the Exe

MEDWAY.

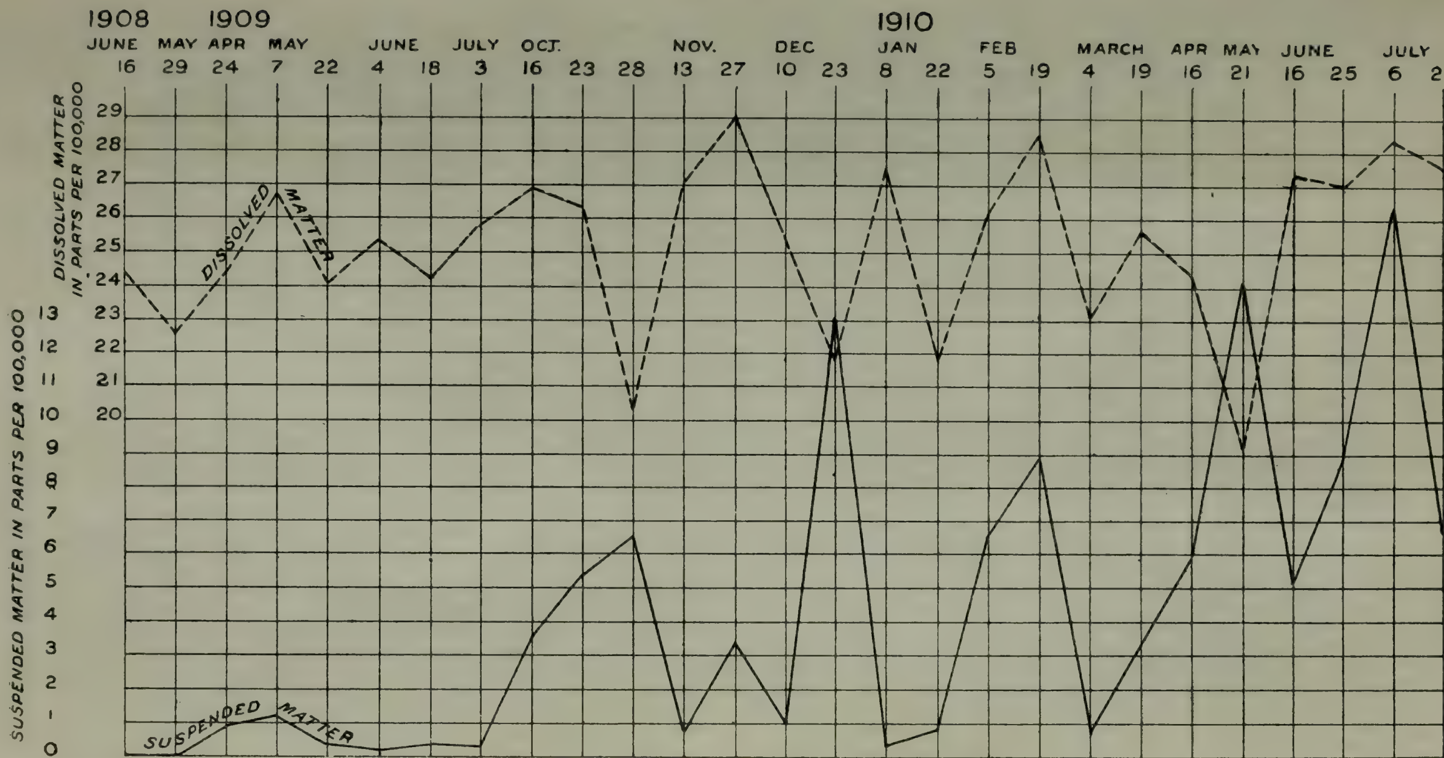


FIG. 20.

corresponding to a gauge-reading of 50 inches is 1480 cusecs, that is 3·38 times the average.

I regret that we have no data for an estimate of the total load carried by the water past the bathing-place at Exeter. Brampford Speke is 4 miles higher up the river and above the entries of the Culm and Creedy, on which streams the observations are too incomplete for an estimate. But it is worth noting what the work of the Exe at Brampford Speke in carrying matter in suspension and solution, added to its work at the bathing-place, amounts to. A calculation has been made by Dr. Owens on the basis that 233,544·559 tons were carried in suspension and solution in $5\frac{1}{4}$ years, and that this amount represents an annual average of 30,755 cubic yards.* This, added to the annual average of amount rolled at the bathing-places, gives a total of 31,908 cubic yards of material removed annually. At this rate it would take 7767 years to lower the surface of the basin 1 foot if the loss were equally distributed over the area.

Such calculations as this are often applied to the denuding work of rivers, but it must be remembered that the erosion is far from being equally distributed, a fact of which the Exe itself supplies one of the simplest examples. For a part of the area drained by it may be described as a dissected plateau, that is, a level, elevated tract which has been so deeply eaten into by streams that the plateau surface survives only in strips. These strips vary in width, but they have this feature in common, that they retain the original level surface which was characteristic of the plateau. Obviously, the effect of denudation upon the surfaces of the strips has been insignificant, but on the other hand the lateral encroachment by streams upon the flanks of the strips has been great, and is still in active progress. Even in the main stream a perfect grade has not been established (Fig. 21, p. 91). These phenomena belong to a stage in the process by which land is reduced to the base level of erosion. It is clear that the fullest surface-relief of which the Exe basin is capable has not yet been attained, and that when that has been reached the rate of erosion will diminish, for the flat-topped strips will become reduced in width, and pass into rounded ridges, while the steepness of gradient which gives the streams their power to erode will be lost. Erosion will be more evenly distributed over the area of the basin, but will diminish in intensity until the base level is reached and it ceases altogether.

In discussing the stage reached by our rivers in a recent address to the Geological Society I used the following words:—

" Few rivers roll material directly into the sea; in fact, no English river is now accomplishing this feat. The conditions for its accomplishment involve a continuously steep gradient down to tide-level. In our rivers the steep gradient is generally confined to the upper reaches; a modified gradient, with correspondingly reduced transporting power in the current, characterizes the middle reaches; while in the lower reaches transportation is replaced by deposition. This condition is due partly to the fact that the river-system has gone far towards reaching what is known to physiographers as 'maturity,' but still more to the sinking of the land which has taken place during and since Neolithic times, and has had the effect of drowning the lower reaches and admitting the tide far inland. A restoration of the land to the level recorded in the Neolithic deposits of the Barry and Southampton docks and in the buried peat-beds of many other estuaries, would go far towards excluding the tide from the lower reaches; but a further elevation would be required to bring about that 'rejuvenescence' which would render our rivers capable of carrying their coarser solid contents clear out to sea.

" The diagrams of the Exe, the Medway, and the Severn (Fig. 21) illustrate

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* On the assumption that a cubic foot would weigh 120 lbs.

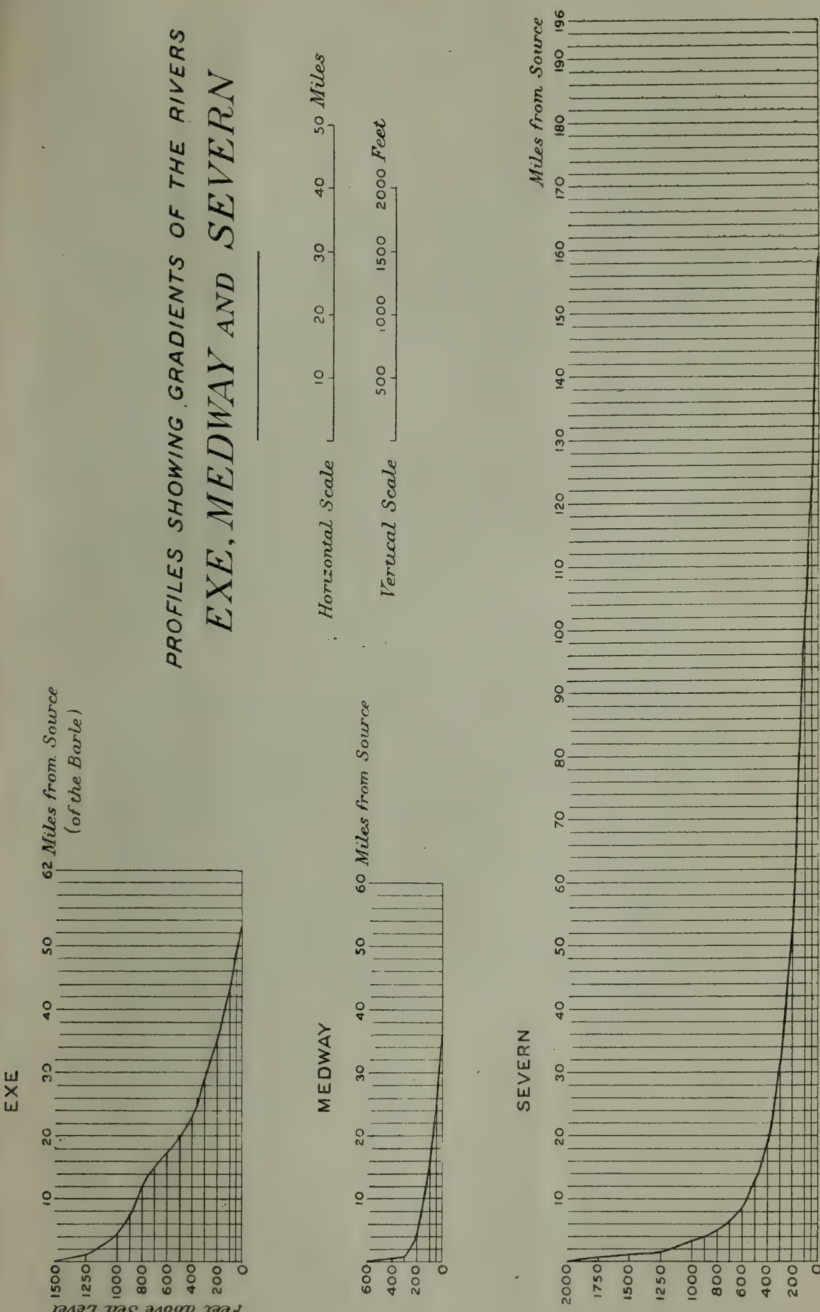
PROFILES SHOWING GRADIENTS OF THE RIVERS
EXE, MEDWAY AND SEVERN
Horizontal Scale
10 20 30 40 50 Miles
Vertical Scale
500 1000 1500 2000 Feet
EXE
62 Miles from Source (of the Barle)
10 20 30 40 50
1500 1250 1000 800 600 400 200 0
Feet above Sea Level
MEDWAY
60 Miles from Source
10 20 30 40 50
600 400 200 0
SEVERN
Miles from Source
10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 196
2000 1750 1500 1250 1000 800 600 400 200 0

FIG. 21.

two types of English river. The points of intersection of the river-bed with the contours shown on the Ordnance maps are plotted at their proper respective distances from the source, the scales being so adjusted as to give a vertical exaggeration of about 105. The Medway and the Severn show a profile which may be taken as typical of English rivers. Tidal waters extend about a third of the total length of the river. A long stretch of gentle gradient follows, increasing in steepness steadily, but with almost imperceptible slowness. Then comes a sudden curve up to the source. Such profiles tell their own tale. Whatever rapids or waterfalls may once have existed, all have eaten their way back to form part of the upper and steeper reaches, leaving behind them an evenly graded channel. In the Exe the case is different; the tidal reach is comparatively short, the middle reach is not only steeper, but is not perfectly graded. The upper reach alone presents the characteristic form, and evidently there is still much to be done in the middle and lower reaches before such perfection of profile as that of the Severn is attained.

"The power of rivers to roll material doubtless varies in different parts of their courses according to local circumstances, but the general rule holds good that the upper reaches of English rivers form the scene of erosion, and the lower reaches that of deposition. It would be interesting, in the case of the Exe, to ascertain how far the geological structure is responsible for the imperfection of the gradient; and secondly, by observing the operations of the river at several points to determine what progress is being made towards the perfecting of it. I will now merely mention that the whole of the upper part of the course is in Devonian rocks, and that the irregularity in the gradient between 900 and 400 feet may be connected with the character of the strata at Hawkridge. The cessation of the steep gradient at 400 feet marks the spot where the river leaves the Devonian, and flows on to the Culm Measure outcrop." *

The investigation which we have now brought to a close was instituted with a view to experimenting on methods which did not involve the erection of costly and more or less permanent apparatus, and the employment of a staff of observers. The erection of weirs or the suspension of cables across the rivers was impossible in view of the difficulties which would have arisen with riparian owners and navigation companies. Apart from the reading of the water-level on the fixed gauges the whole of the work has been carried out by volunteer effort.

The desirability of the objects we had in view has been generally recognized. The Royal Commission on Canals and Inland Navigation of the United Kingdom inserted the following paragraph in their Final Report in 1909:—

"779. We desire to point out, at this stage of our report, how greatly the difficulties of investigations as to water supplies available along the canal routes are enhanced by the absence of any statistical information as to the flows of rivers and streams. Our investigations have shown the necessity, if the canal system of the country is to be improved and extended in the future, of an authority which would have power to collect and tabulate information regarding the flows of rivers and streams, and as to the water supplies available in districts where inland waterways now exist."

In Volume IV. of their Proceedings the Commission also published a map on which the catchment areas of the rivers of England and Wales are reproduced on the same scale from the map which has previously been mentioned (p. 70) as having been published by the Ordnance Survey. They further recommended the appointment of a Waterway Board for Great Britain, and thought it "worthy of careful

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* Anniversary Address by the President, *Quart. Journ. Geol. Soc.*, vol **70**, 1914, pp. xc., xci.

consideration whether the collection of information as to the flows of rivers and streams, and as to water supplies in the districts of Great Britain where there are navigable waterways, should not also be entrusted to the Waterway Board."

Investigations confined for the most part to the relation of run-off to rainfall, and dealing with parts only of a few river-basins, have been carried out from time to time in connection with water-works and other schemes, but there has been no concerted action, such as was contemplated by the Canals Commission. In the absence of such action there seems to be little prospect of our obtaining data for such essential matters as the delimitation of river-basins, the outflow of the rivers and its relation to the rainfall, or a comparison of river-basins as regards their impermeability and quickness of response to rainfall or underground resources in time of drought. In other countries, and notably in the United States, a study of the water resources, and more especially of the resources of the less well-known tracts of the Continent, is regarded as an essential part of the work of exploration. In our own country the case is different. Our rivers, in thickly populated regions, are liable to have water added or abstracted in unknown quantities, while others gain the sea by a multitude of channels which it would be difficult to gauge. There remain, however, a large number which present no such difficulties and which draw their supplies from regions of high elevation and copious rainfall. These must be regarded as valuable assets in the natural resources of the country, and deserve more systematic attention than they have received.

APPENDIX.

TABLE OF DISCHARGE COEFFICIENTS FOR CHANNELS WITH BED AND SIDES OF EARTH.

R	c	C	R	c	C
0·5	0·53	35·7	8·0	0·78	88·0
0·75	0·63	42·6	8·5	0·78	88·9
1·0	0·65	47·9	9·0	0·78	89·7
1·5	0·69	56·0	9·5	0·78	90·5
2·0	0·71	62·0	10·0	0·78	91·2
2·5	0·72	66·6	11·0	0·78	92·4
3·0	0·73	70·4	12·0	0·79	93·4
3·5	0·74	73·5	13·0	0·79	94·4
4·0	0·75	76·1	14·0	0·79	95·2
4·5	0·75	78·3	15·0	0·79	95·9
5·0	0·76	80·2	16·0	0·79	96·6
5·5	0·76	81·9	17·0	0·79	97·2
6·0	0·77	83·4	18·0	0·79	97·7
6·5	0·77	84·8	19·0	0·79	98·2
7·0	0·78	86·0	20·0	0·80	98·6
7·5	0·78	87·0	25·0	0·80	100·3

$$\text{R} = \text{Hydraulic radius} = \frac{\text{area of section}}{\text{wetted perimeter}}.$$

$$c = \frac{\text{mean velocity}}{\text{maximum surface velocity}}.$$

C = Bazin's coefficient in $\text{V} = \text{C}\sqrt{\text{RI}}$.

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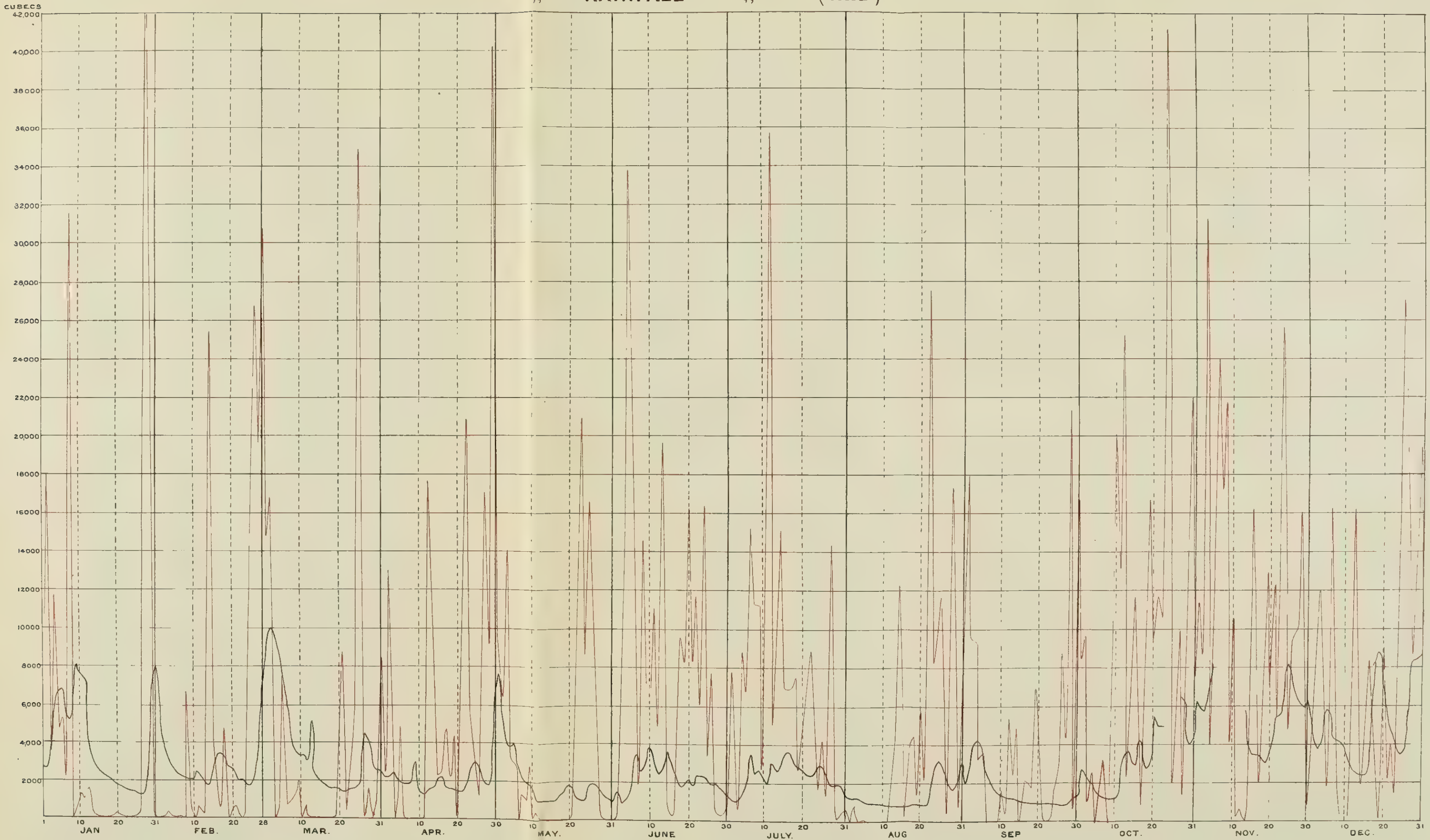
PLATE I.

RIVER SEVERN.

DAILY DISCHARGE CURVE (BLACK)

" RAINFALL " (RED)



1882

RIVER SEVERN

PLATE 2.

DISCHARGE CURVE (BLACK)
RAINFALL ,, (RED)

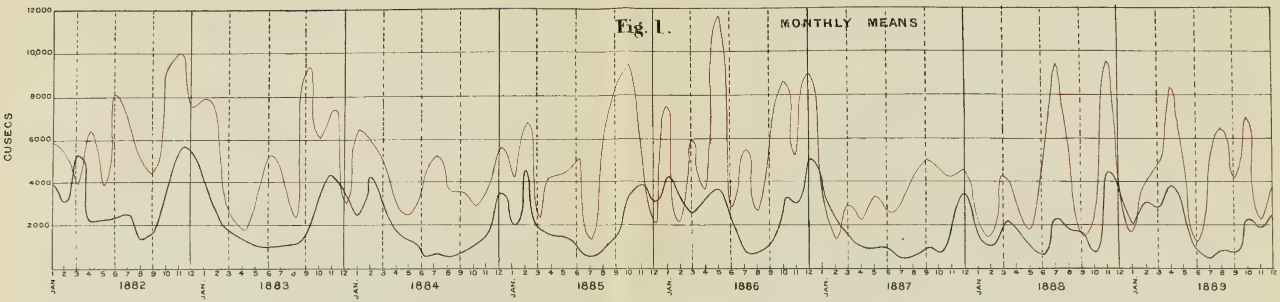


Fig. 1.

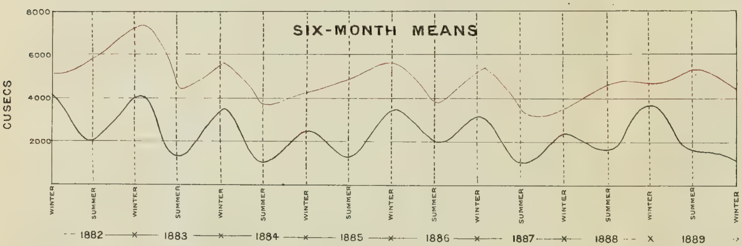


Fig. 2.

WINTER { OCT. NOV. DEC. JAN. FEB. MAR.

SUMMER { APR. MAY. JUNE JULY AUG. SEP.

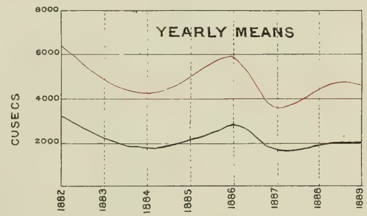


Fig. 3.

PERCENTAGE OF RAINFALL LOST BY ABSORPTION &c.

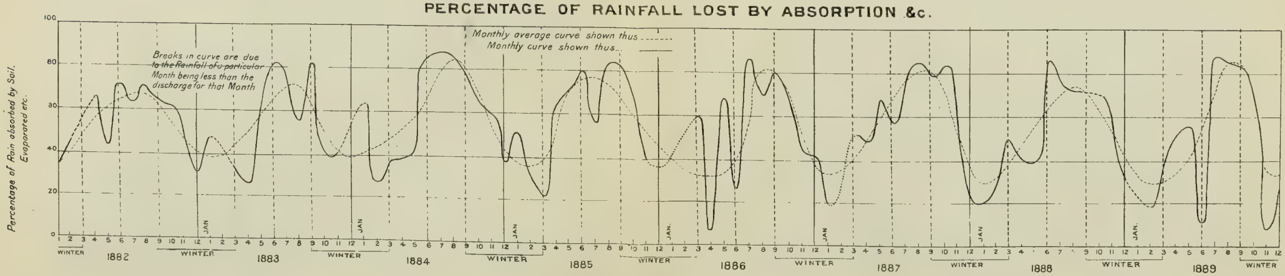


Fig. 4.

RAINFALL MAPS OF THE SEVERN BASIN ABOVE WORCESTER AND VICINITY FOR YEARS 1882-1889 INCLUSIVE.

Area inside Water Parting = 1970·67 Sq. Miles
Actual Positions of Gauges shown thus ○ Centres of Groups shown thus

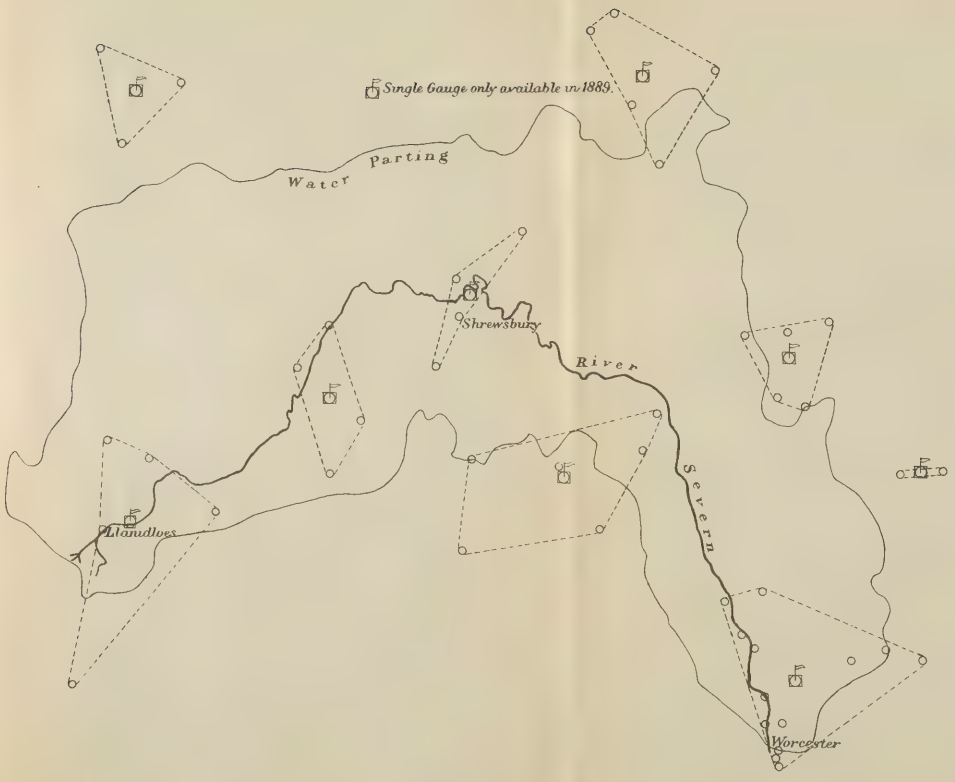


Fig. 1.

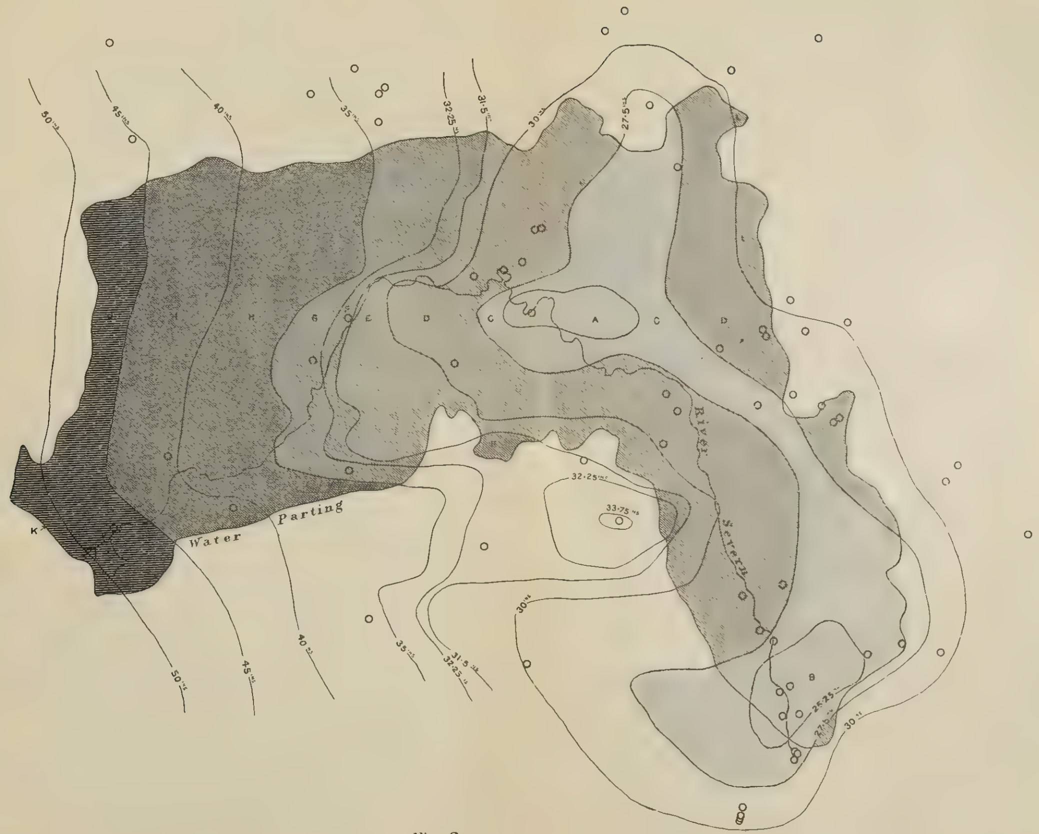


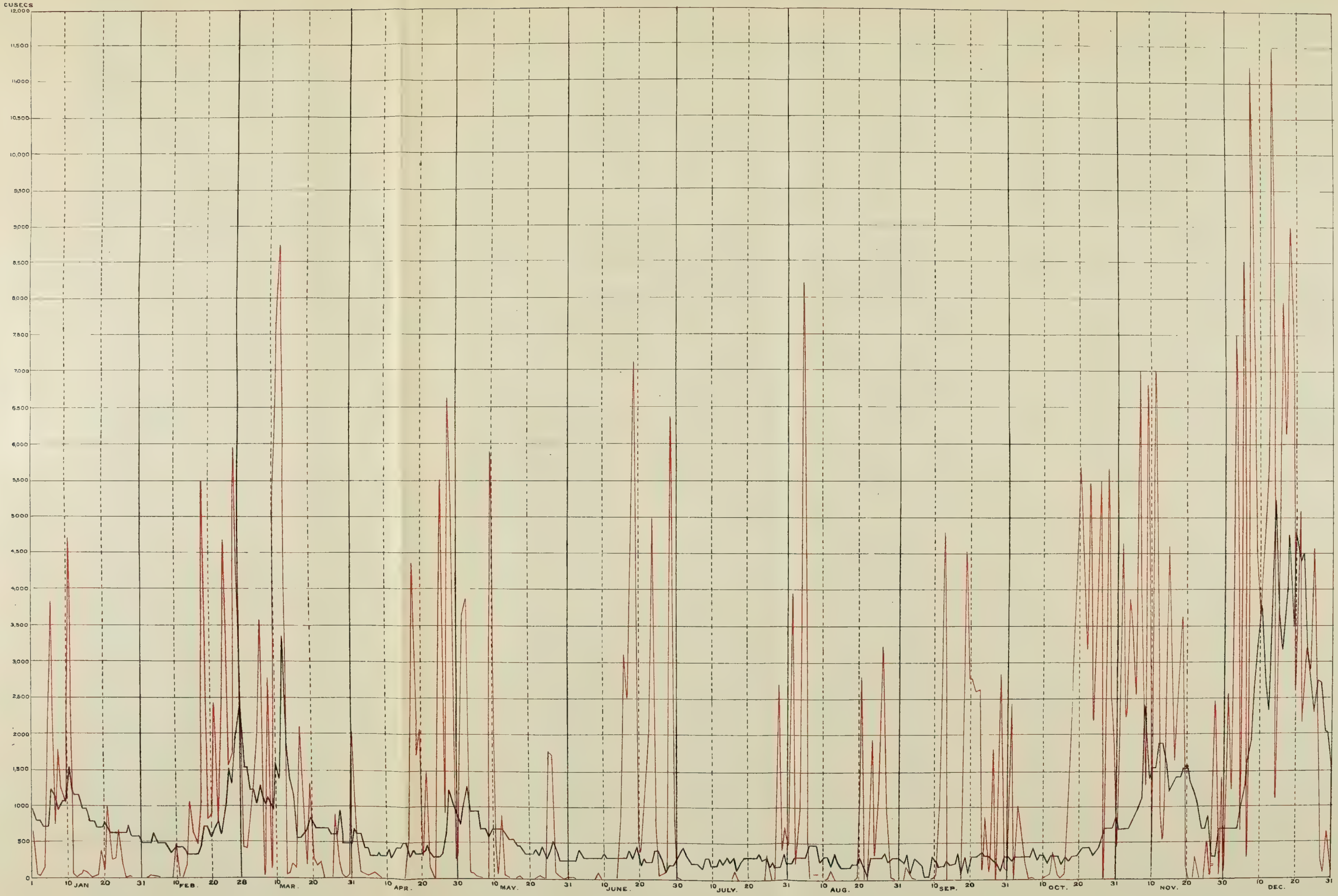
Fig. 2.

RIVER EXE

PLATE 4.

EXETER

DAILY DISCHARGE CURVE (BLACK)
„ RAINFALL „ (RED)



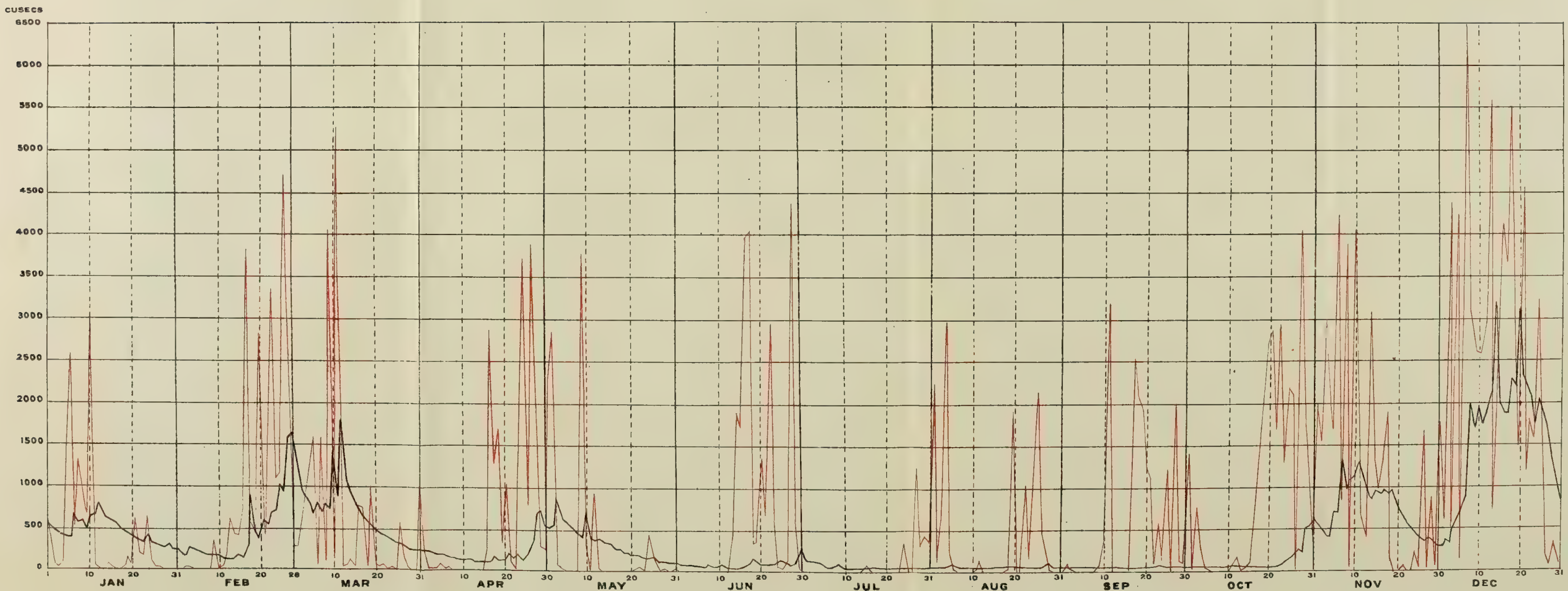
1911

RIVER EXE

PLATE 5.

BRAMPFORD SPEKE

DAILY DISCHARGE CURVE (BLACK)
" RAINFALL " (RED)



1911

RIVER EXE.

DISCHARGE CURVE (BLACK)
RAINFALL „ (RED)

EXETER.

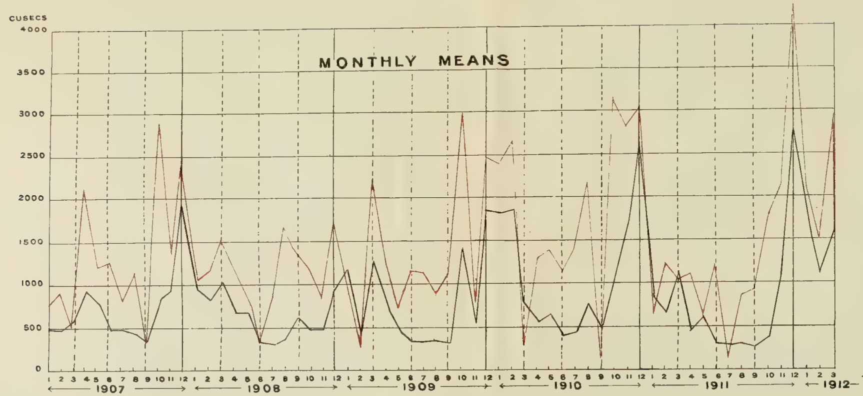


Fig. 1.

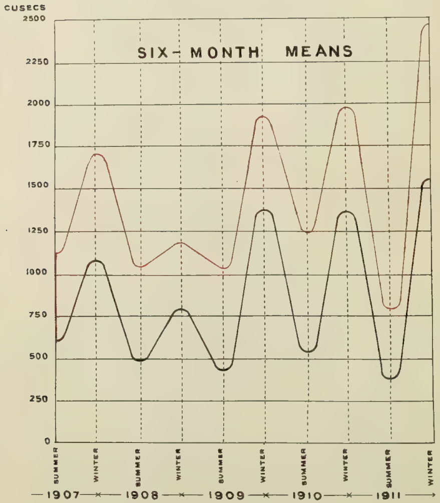


Fig. 2.

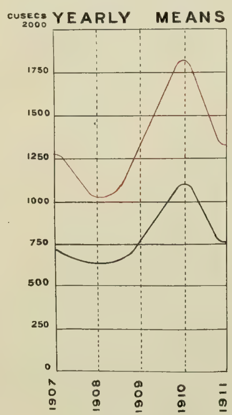


Fig. 3.

BRAMPFORD SPEKE.

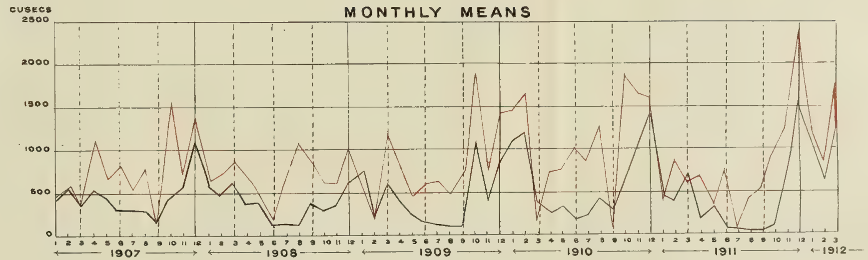


Fig. 4.

SIX-MONTH MEANS

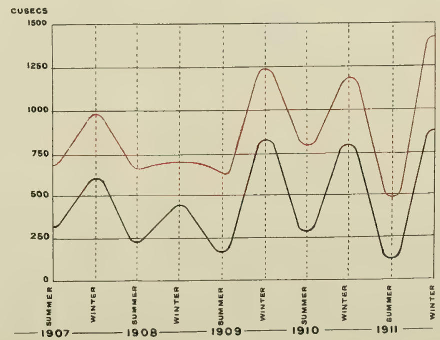


Fig. 5.

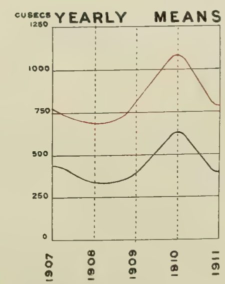


Fig. 6.

RIVER EXE

PERCENTAGE OF RAINFALL LOST BY ABSORPTION &c.

EXETER.

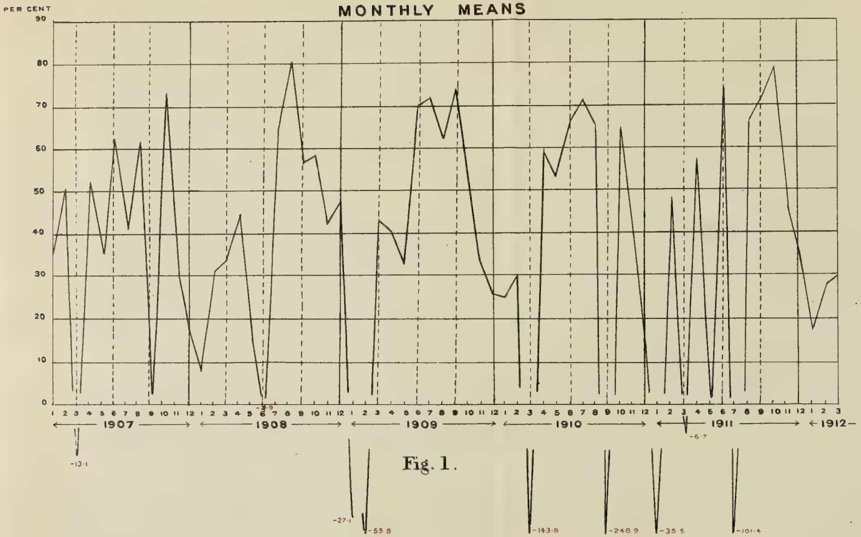


Fig. 1.

BRAMPFORD SPEKE.

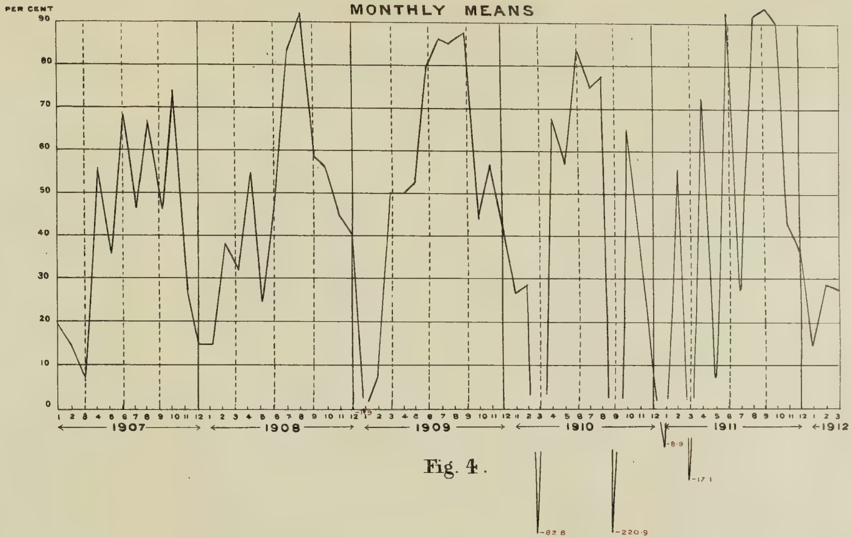


Fig. 4.

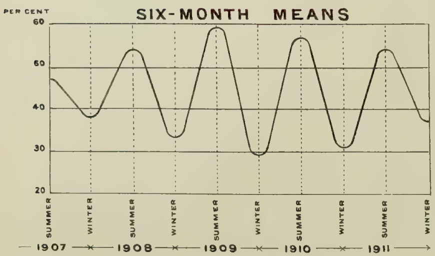


Fig. 2.

YEARLY MEANS

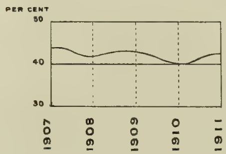


Fig. 3.

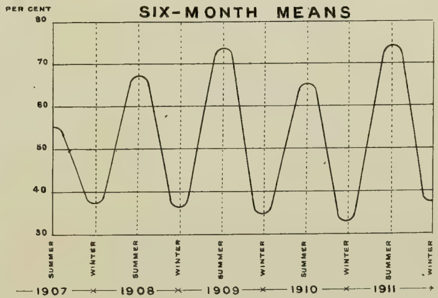


Fig. 5.

YEARLY MEANS

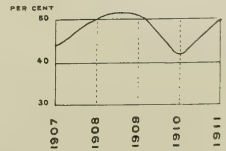
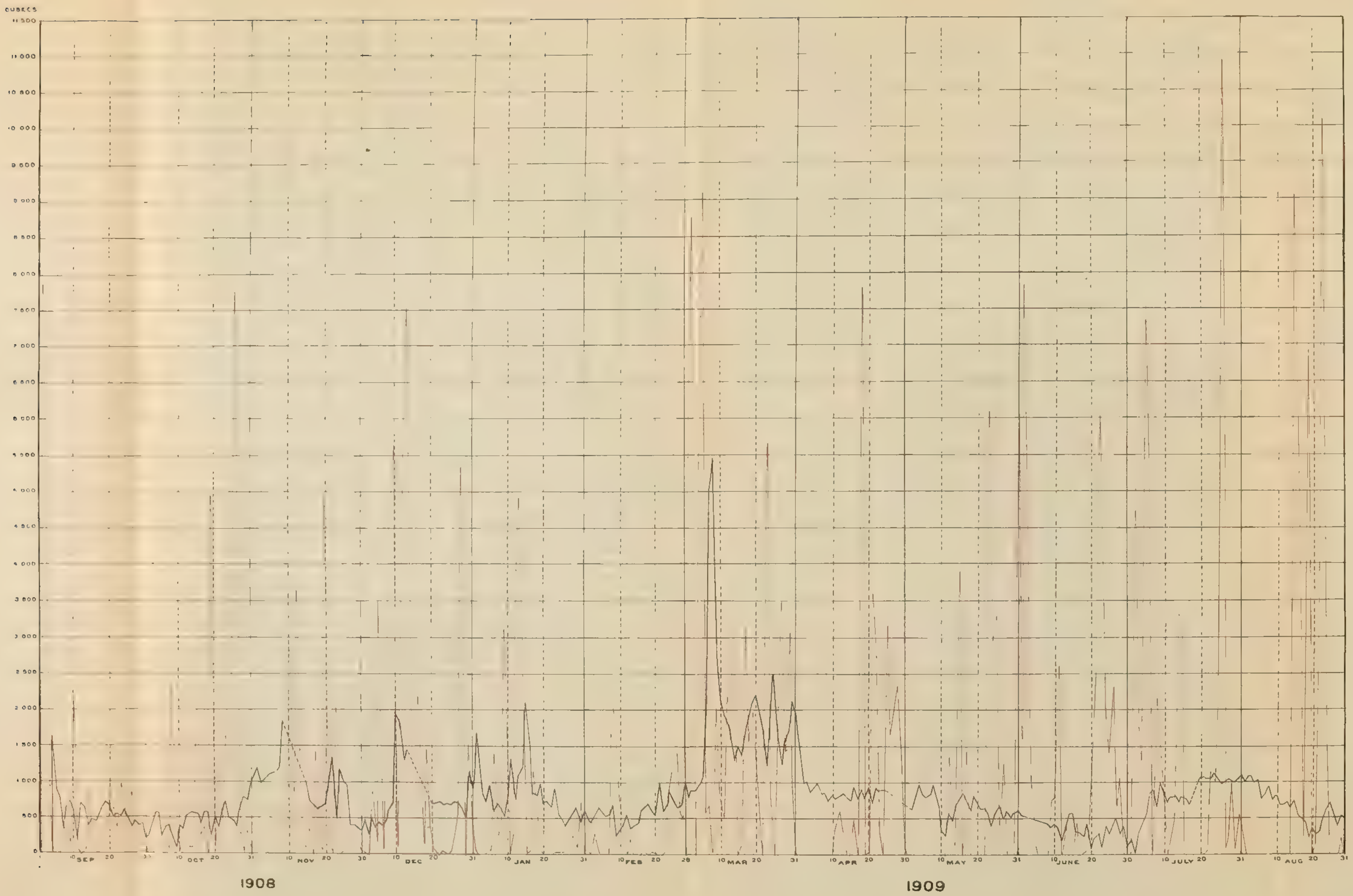


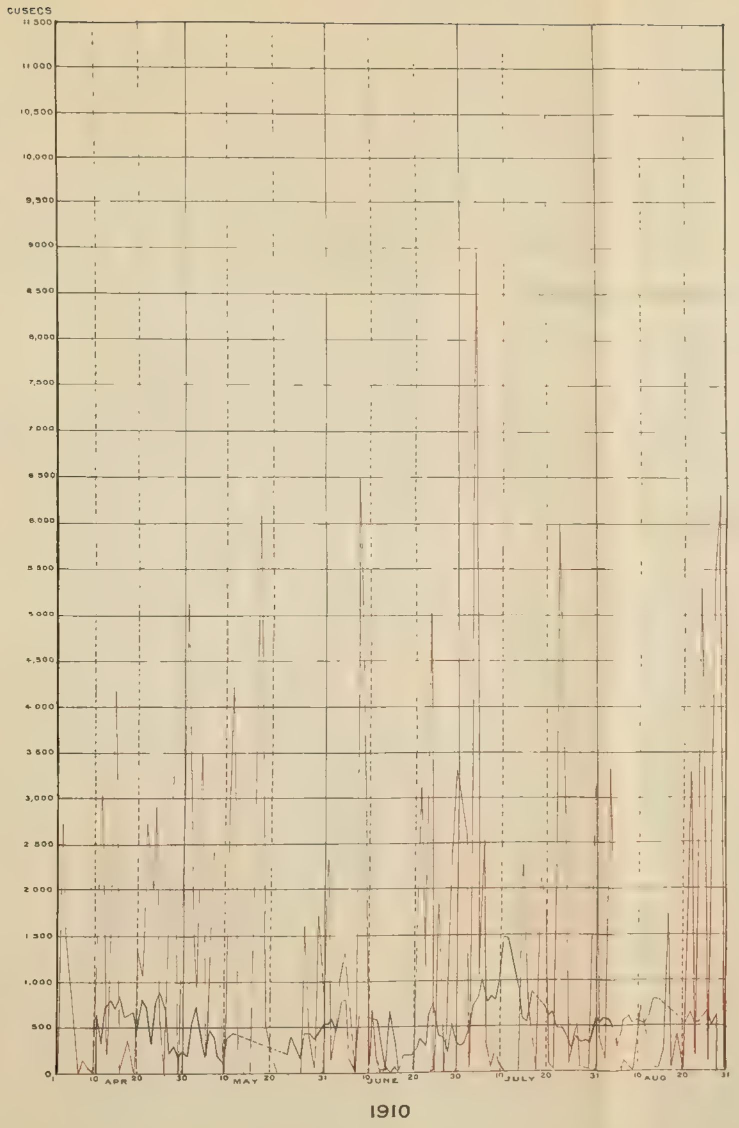
Fig. 6.

PLATE 8.

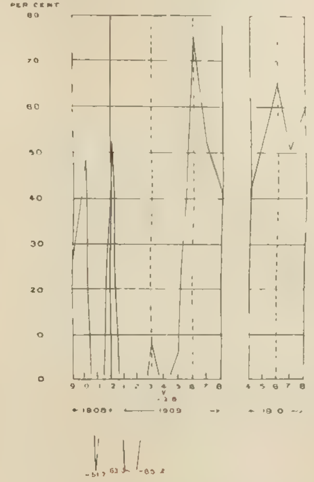
RIVER MEDWAY

DAILY DISCHARGE CURVE (BLACK)
" RAINFALL " (RED

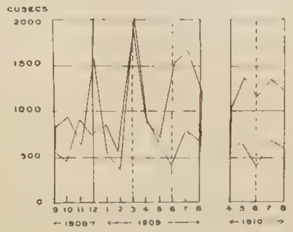


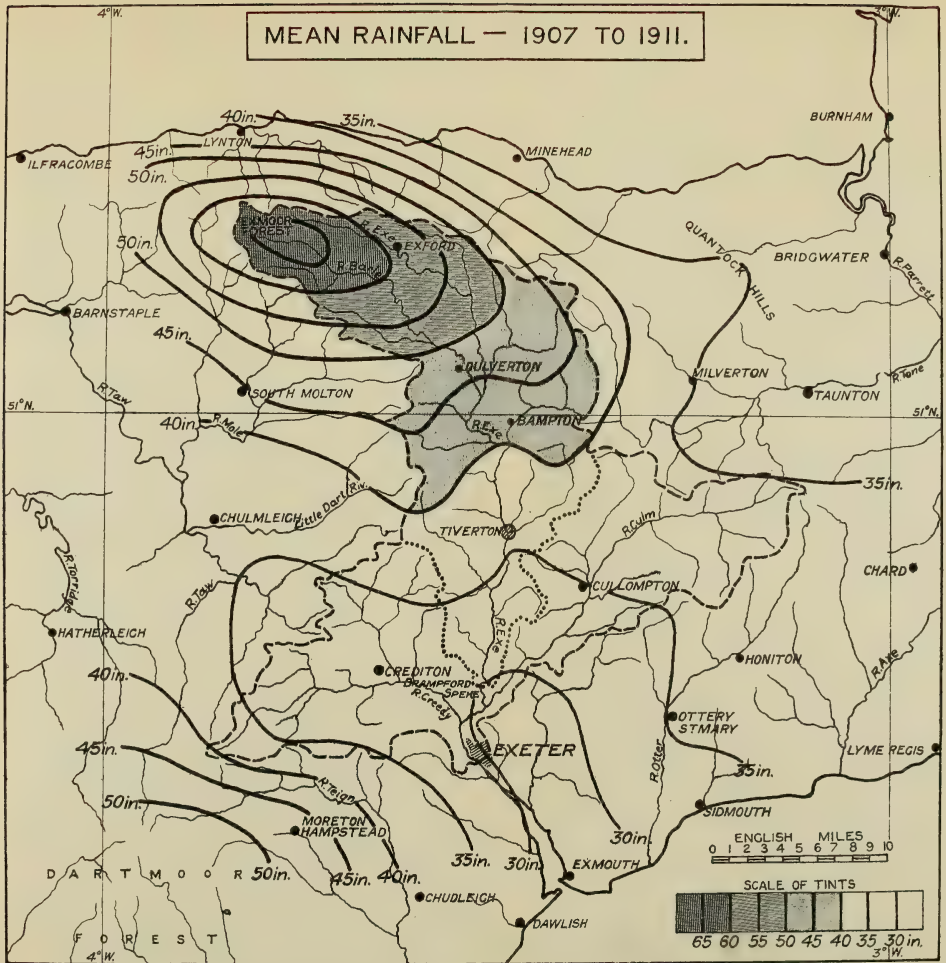


PERCENTAGE OF RAINFALL LOST
MONTHLY MEANS.



MONTHLY MEANS




MEAN RAINFALL — 1907 TO 1911.
4°W.
3°W.
51°N.
ILFRACOMBE
LYNTON
MINEHEAD
BURNHAM
BRIDGWATER
R. Parrett
QUANTOCK HILLS
EXMOOR FOREST
R. Exe
EXFORD
R. Barle
BARNSTAPLE
DULVERTON
MILVERTON
R. Tone
TAUNTON
SOUTH MOLTON
R. Taw
R. Mole
BAMPTON
CHULMLEIGH
Little Dart Riv.
TIVERTON
R. Culm
CHARD
CULLOMPTON
R. Torridge
HATHERLEIGH
HONITON
CREDITON
BRAMPFORD SPEKE
R. Creedy
R. Axe
OTTERY ST MARY
EXETER
LYME REGIS
R. Otter
R. Teign
SIDMOUTH
MORETON HAMPSTEAD
EXMOUTH
CHUDLEIGH
DAWLISH
DARTMOOR FOREST
30in.
35in.
40in.
45in.
50in.
ENGLISH MILES
0 1 2 3 4 5 6 7 8 9 10
SCALE OF TINTS
65 60 55 50 45 40 35 30 in.